AMERICAN FUELS

VOLUME I

AMERICAN FUELS

IN TWO VOLUMES
VOLUME I

BY
RAYMOND FOSS BACON, PH.D., SC.D.,
CONSULTING CHEMICAL ENGINEER, NEW YORK, N. Y.; FORMERLY DIRECTOR OF THE MELLON INSTITUTE OF INDUSTRIAL RESEARCH OF THE UNIVERSITY OF PITTSBURGH

AND

WILLIAM ALLEN HAMOR, M.A.,
ASSISTANT DIRECTOR OF THE MELLON INSTITUTE OF INDUSTRIAL RESEARCH

WITH THE COLLABORATION OF SPECIALISTS

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PREFACE

There has been a considerable output of publications on fuel economy and the better utilization of various forms of fuel, but in preparing the present composite treatise the object of the editors and their collaborators has not been to cover the same ground as works on fuels which are already available. They have attempted to condense into a series of specially prepared chapters the fruits of the experience of specialists, thereby placing in the hands of manufacturers, engineers and chemists a composite book presenting authoritative accounts of the fuels now regarded as technically important in the United States.

In treatises of the customary type dealing with the subject of fuels, definite advice respecting the selection and economic use of fuels, such as will be found in these pages, is given very infrequently. The authors of handbooks in this field have dealt at length with the ordinary classes of solid, liquid and gaseous substances which, when burned with air, evolve heat with sufficient rapidity and in sufficient quantity to be employed as fuels for domestic or industrial purposes; but they seldom provide the industrialist or engineer with such information as will assist him in deciding upon the most suitable fuel to use or the changes to make in the utilization of fuel or of heat in order to get the highest efficiency in plant operation. The attempt has been made by the editors to remedy this omission by embodying in one work the contributions of authorities on all fuels of industrial interest. None of the contributors makes a claim to finality in presenting information regarding the specific fuel whereof he treats, but the technologist is assured that the practice which is indicated therein has been followed with success in existing plants. Of course, the editors are not responsible for opinions expressed by their collaborators, but the names of these experts are a guarantee that no pains have been spared to make the work a faithful record of the present knowledge of American fuels. The editors are grateful to them for their constant coöperation during the preparation of the manuscripts of the chapters of the treatise.

As far as possible, the "catalogue" element has been eliminated, although this is not always an easy thing to do. All engineers and chemists can procure manufacturers' catalogues, and the task which confronted the authors was to select those mechanical appliances of which they have practical knowledge, to give such details as are not readily accessible to the average industrialist, engineer or chemist, and to furnish them with such hints as will enable them to make a wise selection. Progress in fuel engineering has been very rapid during the past decade, and nowhere is care more needed than in securing well-designed and durable equipment for using fuels.

The editors hope that this treatise will be found to give informative summaries of sound practice and the practical details which are generally not to be found in the literature. They ask the indulgence of the reader for any errors or omissions that occur in the present volumes. In a work of this character, covering so large and progressive a field, an early revision will probably be desirable, and the editors accordingly will be grateful for any suggestions with this end in view that may be submitted to them.

Some of the chapters have been written from the viewpoint of men who are enthusiastic advocates of the particular fuels treated. However, this is not an undesirable attitude toward certain newer fuels which have not yet had wide commercial use. It should be understood that it is not the purpose of the editors to endorse or advocate the use of any particular fuel, but to give as many facts as possible regarding the use of all fuels of importance in the United States, that the reader may make an intelligent choice for his particular conditions and needs.

In accordance with the editorial plan outlined above, it would be inappropriate to discuss the geochemistry of coal. The origin of coal, artificial coals, the constitution of coal, and the gases in coal are considered at length by F. W. Clarke in his monumental treatise on "The Data of Geochemistry," 3d ed., 738 *et seq.* William A. Bone's technochemical classic on "Coal and Its Scientific Uses," **1918,** gives in essential outline an account of the present state of science and practice in relation to coal and its various uses. Bone accords extended treatment to the subject of the chemical composition of coal, which is not considered in any detail in the present work. Another subject which is given authoritative discussion by Bone is domestic heating—this has been omitted purposely from *American Fuels*, which, as noted, is intended more for the reference of manufacturers and their technical aids. Bone also considers coal gas as an industrial fuel, a subject which is discussed further by Arthur Mead in *Cassier's Engineering Monthly* for September, **1913**, and by H. S. Taylor in his "Fuel Production and Utilization," **1920**, 89–114.

Since *American Fuels* is a descriptive treatise on industrial fuels and their utilization, the editors had planned originally to devote considerable attention to air supply and measurement of draught, furnace efficiency, and furnace and boiler tests. However, the lack of space has prevented this, and accordingly the reader is referred to F. J. Brislee's "An Introduction to the Study of Fuel," **1912**. It has likewise been necessary to omit a chapter on the measurement of high temperatures; but, fortunately, there is available the composite treatise on "Pyrometry," including the papers and discussion of a symposium on pyrometry held by the American Institute of Mining and Metallurgical Engineers in Chicago, Ill., September, 1919; this volume was published by the Institute in New York in 1920. No space is given to liquid fuel for internal-combustion engines, a subject which is treated by Dugald Clerk in his "Gas, Petrol, and Oil Engine," 2 vol., **1909**; J. S. S. Brame in his "Fuel," **1917**; H. Moore in his "Liquid Fuels for Internal Combustion Engines," **1918**; and others. The reader is also referred to two earlier works in the Mellon Institute Technochemical Series, namely, Bacon and Hamor's "American Petroleum Industry," 2 vol., **1916**, and Hamor and Padgett's "The Examination of Petroleum," **1920**.

The Dayton air-oil gas process is described in Chap. XVII, but the technology of oil gas receives no further attention in this work. The production and application of oil gas are reviewed in *Am. Gas Light J.*, *99*, 272–82 and 294; and the improved Jones process is presented at length *ibid.*, *103* (1915), 23–7.

Next to the waste of valuable byproducts, otherwise recoverable, the smoke nuisance is conceded to be the most serious evil attendant upon the use of raw bituminous coal. But in the present treatise this subject has not been given more than passing attention in appropriate places. For considerations of the smoke nuisance and its abatement, the reader is referred to the following books:

William Nicholson's "Smoke Abatement," **1905**.

W. H. Booth and J. B. C. Kershaw's "Smoke Prevention and Fuel Economy," **1911**; and

J. B. Cohen and A. G. Ruston's "Smoke—A Study of Town Air," **1912**.

He will also find information of value in "Smoke Abatement and Electrification of Railway Terminals in Chicago," the Report of the Chicago Association of Commerce Committee of Investigation on Smoke Abatement and Electrification of Railway Terminals, **1915**; and in the following publications of the Smoke Investigation conducted under the auspices of the Mellon Institute of Industrial Research:

Bulletin 1, "Outline of the Smoke Investigation;" Bulletin 2, "Bibliography of Smoke and Smoke Prevention;" Bulletin 3, "Psychological Aspects of the Problem of Atmospheric Smoke Pollution;" Bulletin 4, "The Economic Cost of the Smoke Nuisance to Pittsburgh;" Bulletin 5, "The Meteorological Aspects of the Smoke Problem;" Bulletin 6, "Papers on the Effect of Smoke on Building Materials;" Bulletin 7, "The Effect of the Soot in Smoke on Vegetation;" Bulletin 8, "Some Engineering Phases of Pittsburgh's Smoke Problem," and Bulletin 9, "Papers on the Influence of Smoke on Health."

RAYMOND FOSS BACON.
WILLIAM ALLEN HAMOR.

CHEMISTS BUILDING, 50 E. 41ST,
NEW YORK, N. Y.
AND
THE MELLON INSTITUTE OF INDUSTRIAL RESEARCH OF THE
UNIVERSITY OF PITTSBURGH,
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CONTENTS

VOLUME I

AMERICAN FUELS

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CHAPTER I

THE COALS OF THE UNITED STATES

By

Marius R. Campbell*

RANKS OF COAL

In this chapter the word "rank" will be used to designate those differences in coal that are due to the progressive change from lignite to anthracite, a change marked by the loss of moisture, of oxygen, and of volatile matter. This change is generally accompanied by an increase of fixed carbon, of sulphur, and probably of ash.† When, however, one coal is distinguished from another by the amount of ash or sulphur it contains, this difference is said to be one of grade. Thus "a high-grade coal" means merely one that is relatively pure, whereas "a high-rank coal" means one that is high in the scale of coals, or, in other words, one that has suffered devolatilization and that now contains a smaller percentage of volatile matter, oxygen, and moisture than it contained before the change occurred.

Within the boundaries of the United States there are all ranks of coal, from the coarse, woody lignite of North Dakota and eastern Montana to the highest rank of anthracite in the fields of eastern Pennsylvania. From the earliest days of coal mining in this country it has been recognized that coals differ greatly, not only in the percentage of ash which they contain, but also in their inherent composition. Although the latter distinction was recognized, little or no attempt was made to determine the reason for the difference or the criteria for fixing the limits of

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* United States Geological Survey, Department of the Interior, Washington, D. C.

† On the origin, development, variations and constitution of coal, see F. W. Clarke's "The Data of Geochemistry," 3d ed., 738–65.

different groups of coals. The first serious attempt in this country to devise a scientific basis for the classification of coal was made by Persifor Frazer, Jr., of the Second Geological Survey of Pennsylvania, under the direction of J. P. Lesley. Frazer* listed most of the commercial coals of the State and then compared the trade distinctions with the "fuel ratio" (the quotient of the fixed carbon divided by the volatile matter of the proximate analysis). He found that there were in use at that time the rank names of anthracite, semianthracite, semibituminous, and bituminous. He found that in practice the fuel ratios of the coals of the different groups overlapped, but he concluded that these ranks might be established with the following limits:

	Fuel Ratio
Anthracite	100 to 12
Semianthracite	12 to 8
Semibituminous	8 to 5
Bituminous	5 to 0

These ranks, with the boundaries fixed provisionally by Frazer, serve very well for Pennsylvania and for the coals of the great Appalachian trough, extending from northern Pennsylvania to central Alabama, but they do not apply to the great mass of western coals, which at that time were of little or no importance. Most of those persons who were instrumental in developing the coal fields of the West originally came from the East, and they carried with them ideas of coal obtained in the eastern fields, which contained high-rank fuel. Not only that, but most of the coals in the Appalachian region and those in the upper Mississippi Valley are of Carboniferous age and hence are very old; but the coals of the West are Cretaceous and even Tertiary in age and hence, when compared with Appalachian coals, are very young indeed. A difference in character was recognized, and as the western coals are generally inferior they were lumped together and called merely "lignite." The term "lignite" is undoubtedly appropriate for many of the low-rank coals of the West, but it is certainly not appropriate for black, shiny coals that show little trace of woody texture and are capable of producing a coke of fairly good quality. Nevertheless such coals were called lignite and relegated to the lowest rank among coals.

Several persons have attempted to devise schemes of classifi-

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* *Pennsylvania Second Geol. Survey Rept.* **MM,** p. 143, 1879.

cation based upon chemical composition by which a certain coal could be referred to its proper place merely by means of its chemical analysis, but so far no scheme of this kind has been devised that is applicable to all ranks of coal. Some scheme like Frazer's suits admirably one part of the column but can not be made to fit the other part. Schemes of this kind are so unsatisfactory that the United States Geological Survey has finally decided that it is practically impossible to classify all ranks of coal according to their chemical composition, and that it is necessary to supplement chemical by other criteria. Accordingly, Frazer's scheme, with some necessary modification to make it agree more closely with modern trade practices, has been adopted for the higher ranks of coals, and physical characteristics have been used for the lower ranks. Thus, in the West no one questions that there is coal of the rank of lignite, but it is difficult, if not impossible, to specify what a lignite is in terms of its chemical constituents. Similarly, in the Rocky Mountain region, where the low-rank coals are abundant, there is no question that there is a difference between brown, woody, or amorphous lignite and shiny, black subbituminous coal, but this difference is one that is not clearly defined by available chemical criteria. There is, however, a marked physical difference, although there is no sharp line of demarcation between them. Thus subbituminous coal is black and shiny, whereas lignite is dull and generally woody in texture; subbituminous coal has a greater heating value and carries less moisture than lignite. Altogether the difference between the two is so marked that they are known by different names in the trade, and for that reason, if for no other, they should be classed differently.

In a like manner the distinction between subbituminous and bituminous is not sharp and does not show in a chemical analysis. Subbituminous coal generally carries more moisture than bituminous, but there are so many exceptions to this rule that it has very little value as a means of distinction. There is, however, one marked difference by which they can always be separated, and that is the difference in their behavior under weathering, and as this difference has a marked effect upon their commercial value and use it seems to be a legitimate criterion for separating them into the two ranks, subbituminous and bituminous. The difference in the effect of weathering is due primarily to a difference in the percentage of moisture in the coal, but, as stated above, the percentage of moisture is variable. Subbituminous coals, however, in general contain more moisture than bituminous coal, and on weathering lose their moisture readily. This loss of moisture results in shrinkage and the formation of incipient cracks, which do not conform to the few joint faces but tend to run irregularly. On the other hand, the bituminous coals generally contain a smaller percentage of moisture, so that they shrink very little when they are suddenly dried. They may be very highly jointed and may fall to pieces readily when mined and handled, but their breakage is due to the inherent weakness of the coal, and the cracks almost invariably correspond with the joint faces.

By using these criteria (part chemical and part physical) it is possible to classify coals and not only to define the general characters of the different groups but to delimit them with considerable accuracy. The United States Geological Survey recognizes the ranks indicated below.

Anthracite.—Anthracite is generally well known and may be defined as a hard coal having a fuel ratio (fixed carbon divided by the volatile matter) of not more than 50 or 60 and not less than 10. Most of it is mined in eastern Pennsylvania, where its peculiar quality is due to regional metamorphism—that is, to the crushing stresses that affected the crust of the earth when the rocks were thrown into the great folds that characterize this region. Small areas of anthracite occur in the West, but generally these coals have been converted to anthracite by the heat of some mass of igneous rock that was thrust into the other rocks while it was in a molten condition. Many such masses take the form of thin sheets, which were forced in between the beds of the other rocks, and consequently for some distance they may lie parallel with the coal beds. If a coal bed is cut by the igneous rock, it may be burned to ashes, made into coke, or converted to anthracite. The product will depend on the presence of air, the intensity of the heat, and the length of time the coal was subjected to the influence of the heated mass. Anthracite is an almost ideal domestic fuel, but it is not well adapted to steam raising unless an absolutely smokeless coal is needed. Many people believe that anthracite has greater heating value than any of the other ranks, but this is not true. Largely on account of its low heating power anthracite is not an economical fuel for steam raising or for use in general manufacturing.

Semianthracite.—Semianthracite is also a hard coal, but it is not so hard as true anthracite. It is high in fixed carbon, but not so high as anthracite. It may be defined as a hard coal having a fuel ratio ranging from 6 to 10. The lower limit is uncertain, as it is difficult to say where the line should be drawn to separate "hard" from "soft" coal and at the same time to divide the two ranks according to their fuel ratio. Some hard coals of the anthracite type have a fuel ratio as low as 6.5 or 7, whereas some of the soft coals have a fuel ratio as high as 7 or perhaps more. For this reason it is probable that fuel ratio alone can not be depended upon to separate these two ranks, but that physical properties also may have to be taken into consideration. The change of ordinary soft coal to semianthracite is due to the same causes that produced anthracite, except that the process has not been carried so far in semianthracite, possibly because the action has not been so intense. There is very little semianthracite in this country, so it is only a small factor in the coal trade. Such semianthracite as is mined reaches the consumer generally under the name "anthracite" and is masquerading under false colors.

Semibituminous.—The name "semibituminous" is exceedingly unfortunate, as literally it implies that this coal is half the rank of bituminous, whereas it is applied to a kind of coal that is of higher rank than bituminous—really superbituminous. Semibituminous coal may be defined as coal having a fuel ratio ranging from 3 to 7. Its relatively high percentage of fixed carbon makes it nearly smokeless when it is burned properly and consequently most of these coals go into the market as "smokeless coals." The best coal of this type has a heating value greater than that of any of the other ranks and is consequently best adapted to raising steam and to general manufacturing that requires a high degree of heat. It is regarded as the best coal for steamship and especially for naval use, as it is nearly smokeless and requires less bunker space per unit of heat than other coals. The coal is generally minutely jointed and is therefore tender and friable. In fact, it is so friable that in mining a large percentage of fine coal is produced, and in transportation many of the lumps are broken to pieces, so that by the time it reaches the consumer, especially if it has been transshipped, it is generally in small pieces. This fineness is by many regarded as detrimental, because the public is accustomed to lump coal which will stand transportation without crushing, but when this coal is used with mechanical stokers and with a grate adapted to its use the fineness of the coal is not disadvantageous. The great bulk of this kind of coal is in the eastern fields, but some is found in the West, where it has been subjected to a slight amount of regional metamorphism or has been heated by some igneous mass.

Bituminous.—The term "bituminous," as generally understood, is applied to a group of coals having a maximum fuel ratio of about 3, and hence it is a kind of coal in which the volatile matter and the fixed carbon are nearly equal; but this criterion can not be used without qualification, for the same statement might be made of subbituminous coal and lignite. As noted before, the distinguishing feature which serves to separate bituminous coal from coals of lower rank is the manner in which it is affected by weathering. Bituminous coal is only slightly affected chemically by weathering unless it is exposed for many years, and then, although it consists of small particles, each particle is a prismatic fragment, whereas coals of lower rank break into thin plates parallel with the bedding.

The definition given above might not indicate that the bituminous rank is a large one, but when it is examined critically it is found to contain a great variety of coals—coals having really little in common with one another. Many attempts have been made to subdivide this great group, but so far no scheme proposed has met with general approval. Many of the better coals of this group will coke or are being coked, but coking coals are not limited to the bituminous rank, for some of the best coke made in the United States is produced from semibituminous coal. Not only is the upper limit of the coking group uncertain, but the lower limit is equally difficult to determine. If the coking property had some definite relation to the chemical composition of the coal as it is at present determined, there might be some hope of establishing a class of coking coals by chemical analysis, but no one can say just why a coal will coke, so an actual test in an oven is required to determine whether or not a coal will coke.

Gas coals have been in great demand and such coals must be high in volatile matter, so as to make on distillation a large volume of gas; and as this gas must be relatively free from sulphur the coal from which it is made must contain a very small percentage of that element. In recent years the making of gas for illuminating and heating has undergone a great change, water gas largely taking the place of the gas distilled from coal; and as this gas requires no particular quality of coal, the demand for "gas coals" has been greatly reduced and probably in the near future will disappear.

Cannel coal is very rich in volatile matter, is generally high in hydrogen, and therefore burns with a great heat and a long flame. It is essentially a gas-making coal and in the early days was used extensively for this purpose, as well as for the distillation of oil. As a source of oil it could not compete with petroleum derived from wells, and soon after oil was discovered in the earth in 1859 the business of distilling oil from coal in this country was discontinued. Cannel coal owes its richness to the fact that it is composed almost entirely of the spores, spore cases, seed coats, and resinous or waxy products of such plants as lived at the time of the existence of the coal swamp. In such swamps, as in those of today, there was doubtless in places open water, into which the spores and seed cases floated and, becoming water-logged, sank to the bottom and in time produced cannel coal. The absence of woody material in such coal gives it a regular texture and grain that are not found in any other coals. As a result, it breaks like glass, with a conchoidal or shell-like fracture, and owing to its richness in inflammable material the best of it will ignite readily when a lighted match is held in contact with a small splinter of it. As the nature of cannel coal is due to the kind of material of which it is composed, it follows that there may be all kinds of cannels, corresponding in a general way with the various ranks of coals. Ashley* has recently proposed the following classification of cannel coal:

1. Subcannel coal:
    (*a*) Brown subcannel, or brown coal of lignite rank.
    (*b*) Black subcannel, of subbituminous rank.
2. Cannel coal, of bituminous rank:
    (*a*) Boghead cannel (fuel ratio less than 0.5).
    (*b*) Typical cannel (fuel ratio between 0.5 and 1).
    (*c*) Lean cannel or semicannel (fuel ratio more than 1).
3. Canneloid, semibituminous coal, semianthracite, or anthracite.

Cannels which are of the rank above bituminous have lost their original richness and therefore do not deserve to be called cannels.

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* ASHLEY, G. H., "Cannel coals in the United States," *U. S. Geol. Survey Bull.*

Other kinds of coal, such as "block" and "splint," are recognized in the trade, but the characteristics of these coals are physical and are found in only a small group of coals. Some of the "block" and "splint" coals are very hard, almost as hard as anthracite, but they are generally woody in texture and contain much mineral charcoal. They are valuable coals in the market, but usually their development is so local that they are not of much importance in a general classification of coal.

As the great group of bituminous coal includes all grades from the poorest western bituminous coal to the highest-rank coal in the Appalachian region, exclusive of the semibituminous coal, the writer has, for convenience, divided the group and represented it on the general map of the coal fields of the United States in two colors—one indicating all coals having, in the air-dried sample, a calorific value (in British thermal units) of more than 12,500, and the other indicating all bituminous coals having, in the air-dried sample, a calorific value of less than 12,500. This is a practical separation according to heating value, which, after all, is the principal criterion for determining the relative values of coals.

Subbituminous.—The term "subbituminous" is adopted by the Geological Survey for what has generally been called "black lignite," a term that is objectionable because the coal is not lignitic in the sense of being distinctly woody, and because the use of the term seems to imply that this coal is little better than the brown, woody lignite of North Dakota, whereas many coals of this rank approach in excellence the lowest grade of bituminous coal. Subbituminous coal is generally distinguishable from lignite by its black color and its apparent freedom from distinctly woody texture and structure, and from bituminous coal by its loss of moisture and the consequent breaking down or "slacking" that it undergoes when subjected to alternate wetting and drying. As the percentage of moisture is an important matter in buying and shipping coal, and as the slacking on exposure to the weather makes it necessary to ship in box cars and to guard carefully against spontaneous ignition, there is a great commercial difference in these two kinds of coal which the Geological Survey has recognized by putting them in different ranks. Despite the many drawbacks in the shipment and use of subbituminous coal it has found a ready market in much of the western country, because it is a very clean domestic fuel and ignites with little difficulty.

Subbituminous coals differ considerably in chemical composition and in physical appearance. Some are banded like much of the bituminous coal, and some are essentially cannel in physical and chemical make-up. In general, the Cretaceous and younger coals of the West contain a smaller percentage of sulphur than the older coals of the East, and as some of them are high in volatile matter they would doubtless be excellent coals for making gas, either illuminating gas or producer gas for generating power.

Lignite.—The term "lignite," as used by the Geological Survey, is restricted to those coals which are distinctly brown and either markedly woody or claylike in their appearance. They are intermediate in quality and in development between peat and subbituminous coal. As the moisture of lignite as it comes from the mine generally ranges from 30 to 40 per cent, its heating value is low; and the consumer can not afford to pay freight for any great distance on so much water. Also it parts with much of this moisture very readily when exposed to the weather and so falls to pieces or slacks much more readily and completely than subbituminous coal. On this account it is more likely to ignite spontaneously and must be handled even more carefully than subbituminous coal and stored in a place where it will not be exposed to alternate wetting and drying. Lignite is mainly marketed near the mine, as a domestic fuel, but at a few places in North Dakota and Texas it is shipped to nearby towns and used for general manufacturing purposes.

At the Government testing plant at the St Louis Exposition, North Dakota lignite was found to be an excellent fuel for making producer gas, and probably in the future it will be used to a far greater extent for producing power than it has been in the past. it is possible that large producer plants may be erected at the mines and the lignite converted into electric energy and delivered by long-distance transmission lines to towns within a radius of 200 miles or to the railroads in this region or in contiguous territory. Lignite has recently been used in powdered form, and it may possibly be better utilized in this way. As some of the Texas and Arkansas lignites are in effect undeveloped cannel coals, it seems possible that when the supply of petroleum is much less than the demand, the lignite may be used for the distillation from it of oil and the various by-products that are now obtained in Scotland from oil shale. Lignite can also be manufactured into hard briquets, which make an excellent fuel, but so far the cost of manufacture has been prohibitive.

Comparison of the Different Ranks.—Figure 1 is a graphic representation of the proximate chemical composition of the various ranks of coal and of their heat-producing values. The lower diagram shows the fairly regular increase in fixed carbon from lignite to anthracite, though it must not be supposed that the lines for all coals are as simple as those shown in the diagram. The analyses upon which the diagram is based are, however, actual analyses selected from those given in the table at the end of this introduction. Number 1 represents the analysis of a typical North Dakota lignite which, as it comes out of the mine, has a moisture content of about 40 per cent. It also contains about 5.5 per cent. of ash, but as ash varies irregularly without regard to the rank of the coal the analysis has been recalculated to the ash-free basis, thus eliminating ash from consideration. All the other analyses have been similarly recalculated. Number 2 represents a subbituminous coal from Wyoming, having a moisture content of 23.4 per cent.; Nos. 3, 4, and 5 represent various ranks of bituminous coal, the lowest one being from Indiana, the second from Ohio, and the third, or highest, from the Pittsburgh district of Pennsylvania; Nos. 6 and 7 represent semibituminous coal from the Windber district of Pennsylvania; No. 8 represents semianthracite; and No. 9 represents some of the best anthracite of the Pennsylvania region. The diagram shows clearly that the fixed carbon increases very markedly from lignite to anthracite; that the moisture of the higher-rank coals is small and about the same quantity in each, but increases rapidly from medium-rank bituminous coal to lignite; and that the greatest development of volatile matter is not at either end of the series but in the lower ranks of bituminous coal.

The upper diagram represents the heat value of the same coals on a similar ash-free basis. There is a very general misconception regarding the heat value of anthracite as compared with that of lower-rank coals. Many persons think that because anthracite commands a higher price it must necessarily be a better heating coal than the soft varieties, but this diagram shows conclusively that it is not and that the best coal for heat production is No. 6, or low-rank semibituminous coal. Anthracite commands a higher price than soft coal because of its suitability for domestic use and because of its freedom from smoke, soot, and waste.

From the diagram it might be inferred that the heat value of a coal depends directly upon the amount of fixed carbon that it contains, but this can not be true, for the heat value of pure carbon is only 14,580 B.t.u.,[1] whereas coal No. 6 has a heat value of 15,480 B.t.u. Coal derives its heat value mainly from two elements, carbon and hydrogen, the carbon having a heat value of 14,580 B.t.u. and the hydrogen a heat value of 62,000 B.t.u.* The greater heating power of the low-rank coals as compared with anthracite is due to the fact that these coals contain a considerable quantity of available hydrogen,† which when burned produces a much greater heat than the same weight of carbon.

Either diagram well illustrates the slight value of lignite as compared with the higher-rank coals and makes it possible to understand that Pennsylvania and West Virginia coal can be hauled by rail to Lake Erie, shipped by vessel to Duluth or Superior, hauled 400 or 500 miles inland, and then sold in direct competition with lignite mined in the vicinity.

CLASSIFICATION OF THE COAL AREAS OF THE UNITED STATES

For convenience in describing the areas underlain by coal-bearing rocks, some scheme of names and classification of areas is essential. Although coal areas might be subdivided or combined indefinitely, the Geological Survey recognizes four classes, which, beginning with the smallest, are called district, field, region, and province.

Coal District.—"Coal district" is a term applied only to developed coal areas. It is already in common use in the trade for an area in which mining has been developed around a fairly definite center, but it also has been loosely used as synonymous with "coal field." A district is generally small, and the term is restricted to areas in which mines are developed continuously on a given bed or beds, and the coal is generally known in

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* Richards, J. W., "Metallurgical Calculations," p. 16, 1906.

† S. W. Parr ("The Composition and Character of Illinois Coals," *Illinois Geol. Survey Bull.* 3, p. 37, 1906) defines available hydrogen as follows: "By available hydrogen is meant that part of the hydrogen content which is free to enter into combination with oxygen for the production of heat, as distinct from that hydrogen present which already has . . . the necessary equivalent oxygen for the formation of water, and consequently [is] noncombustible."

the trade by some distinguishing feature, such as a trade name, or by some physical characteristic upon which it is advertised and sold. Districts are generally named from the leading town in them, or from the town at which mining first started or which first achieved distinction in producing this particular kind of coal. From the very nature of the case districts are small, but it is not possible to set definite limits to the area that should be classed as a district.

Coal Field.—A coal field is an area of coal-bearing territory next larger than the district. Its recognition is based less upon trade practices and uses than that of a coal district, and therefore it has more of the natural features to characterize it. The term "field" is at present used very loosely, and in many ways it is not advisable to attempt its close restriction. As used by the Geological Survey, it is applied to an area generally larger than a district, but still to a well-defined compact area. In this respect it differs from "region," the term for the next higher division. Small areas or basins that are separated from one another or from the main coal area are called fields, especially if their coal is of fairly uniform composition and value. "Field" is also applied to a certain area which has become prominent because of the kind of coal it produces, but which is not necessarily limited to certain centers of production. Some of the best-known fields of this class are the Pocahontas field of Virginia and West Virginia, the New River field of West Virginia, the Georges Creek field of Maryland and West Virginia, and the Windber field of Pennsylvania. These fields have definite outlines, corresponding with the extent of the bed or beds of coal upon which the field was established or with the limits of coal of a certain quality that influences its sale and use. In large areas of coal-bearing rocks, like that of Illinois, there are many districts or centers of production, but it is also necessary to recognize the larger divisions corresponding with those just mentioned. In Illinois, however, there are no well-defined limits depending on quality of coal or upon natural features, for the region is fairly well and uniformly developed and the quality of the coal does not vary markedly throughout the State. Under such conditions it would be of little value to mark off definite fields, and they would not be used by many; therefore it has been decided that in such areas fields may be recognized as a matter of convenience and hence may vary in different reports, for a division that would be convenient to one person would not necessarily suit the needs of another. It is therefore proposed to consider such a State as Illinois as made up of an indefinite number of coal fields, the limits of which should be defined by the person making the subdivision, and the limits made by one person should not necessarily agree with or control those made by another.

Coal Region.—As a matter of convenience, coal fields may be grouped into larger divisions called "regions." Such grouping is generally designed to bring together coal fields that have some feature or features in common, thus enabling them to be considered as a whole or separately as the problem may demand. The most striking subdivision of a region is in Colorado and New Mexico, where the great area of coking coal in the eastern parts of these States extends across the line from one State into the other. The Colorado portion is well known as the Trinidad field and the New Mexico portion is equally well known as the Raton coal field. Both names are appropriate and needed, but in many discussions it is necessary to consider them together as a unit, for they are as nearly a unit as it is possible for two coal fields to be. For this reason they are here considered together as the Raton Mesa coal region. Likewise, many other areas are essentially a combination of fields and therefore should properly be classed as regions. Good examples are the anthracite region of Pennsylvania; the western coal region in Iowa, Missouri, Kansas, Oklahoma, and Arkansas; and the numerous deep basins of the Rocky Mountain States.

Coal Province.—As fields are grouped into regions, so regions are grouped into much larger divisions, called "provinces." These, as shown on the accompanying map, are the Eastern province, Interior province, Gulf province, Northern Great Plains province, Rocky Mountain province, and Pacific Coast province. The grouping into provinces is made largely for convenience in considering broad questions of geologic age, geologic structure, quality of coal, and transportation. In a province, as in a smaller division, there is a certain amount of unity in the physical features of the coal fields of the province or in the quality of the coal. Some provinces contain all ranks of coal, and the fields are grouped together because of their geographic positions, their structural features, or the age of the coal beds.

THE COAL AREAS

Eastern Province.—The Eastern coal province contains probably nine-tenths of the high-rank coal of the country. It is considered as made up of the anthracite regions of Pennsylvania and Rhode Island, the Atlantic coast region of Virginia and North Carolina, and the great Appalachian region, which embraces all the bituminous and semibituminous coal of what is generally known as the Appalachian trough.

The Rhode Island anthracite region, although known since 1760, is of little economic importance, for the coal has never been mined for a long period on a commercial scale, and judging from its composition and the metamorphism of the surrounding rocks, it seems doubtful whether it will ever have more than a local value, if it is worked at all. The coal is more highly metamorphosed than that of Pennsylvania, so that some of it is mined and sold as graphite. It also carries a large percentage of ash, which makes it an expensive fuel to mine and to use.

The Pennsylvania anthracite coal region is so well known that it needs little mention here. In the trade generally the anthracite region is considered as made up of four fields known as the Northern, Eastern Middle, Western Middle, and Southern. In 1914 these fields together produced 90,821,507 short tons, or 99.9 per cent. of the anthracite mined in the United States.

The Atlantic Coast region is of very little practical importance at the present time, for its coal beds are worked either not at all or on a scale so small as to be negligible. The Richmond field or basin, however, has the distinction of being the scene of the first development of bituminous coal in this country, mining having been begun there in 1787. The coal is generally of high rank, some being semianthracite; but the conditions of mining are not good, and the coal can not at present compete with the better coals of the Appalachian region.

The Appalachian region is the greatest storehouse of high-rank coal in the United States, if not in the world. This near-by almost inexhaustible supply of high-grade fuel has been the foundation of the development of the blast furnaces, the great iron and steel mills, and the countless manufacturing enterprises of the Eastern States. The Appalachian region is a compact area of coal-bearing rocks, which in general lie in a deep trough. The trough shape is well marked in its northern part, and the middle line or axis runs nearly through Pittsburgh and thence southwestward to the vicinity of Huntington, W. Va., on the Ohio River. The lowest coal bed, if present in the deepest part of the trough, would be about 2,000 feet below the surface. The rocks in this great trough are thrown into a large number of minor wrinkles or anticlines (upfolds), especially on its southeastern side. These small folds generally bring to the surface the harder rocks just beneath the coal-bearing beds, and consequently they form ridges or mountains, as they are called in Pennsylvania and West Virginia. These die out toward the southwest, but they exert a marked effect upon the coal beds exposed at the surface as far south as Kanawha River. In southern Virginia and Kentucky the trough flattens very decidedly, and as a consequence the coal beds are not so deep, but their outcrops cover a wider territory. In Tennessee the trough character is scarcely apparent and the coal-bearing rocks appear to be nearly horizontal but are broken up by several small folds similar to those noted in the northern part of the region. The effect, however, is very different, for owing to the flatness of the rocks the streams have cut away the upbending folds, leaving great longitudinal valleys instead of anticlinal ridges, and narrow, flat, intervening troughs of coal-bearing rocks. The same kind of structure, except that the troughs are more pronounced, is seen in the coal fields of Alabama, but toward the southwest the rocks gradually descend, and near Birmingham they begin to pass beneath the later rocks (Cretaceous) that were deposited on the Gulf Coastal Plain. This cover becomes deeper and deeper toward the southwest, until, in the vicinity of Tuscaloosa, the coal-bearing rocks disappear and nothing is in sight but the soft sand and clay of the younger formations.

Along the western margin of the Appalachian region the coal beds dip very slightly toward the east and there are no outliers of any consequence, but on the eastern margin the rocks are much more severely folded and there are many synclines (downfolds), which, by the cutting back of the river valleys, have been separated from the main area and now form isolated natural fields. Among the most prominent of such outliers on the east side are the Broad Top field, in central-southern Pennsylvania; the Georges Creek and Upper Potomac basins, in Maryland and West Virginia; the Lookout Mountain field in Georgia and Alabama; and the Coosà and Cahaba fields, in Alabama. There are also a number of long, narrow outliers in southern Virginia, which properly do not belong with the Appalachian region but which for convenience will be so classed. These fields contain thin and irregular coal beds of Mississippian ("Lower Carboniferous") age. They are the only coals of this age and are the oldest coal beds of commercial importance in the country. Many of them are of high rank, but on account of their irregularity and impurity they have not been extensively developed.

The coal of the Appalachian region is generally of high rank but shows considerable variation, mainly in an east-west direction. In the reports of the second Geological Survey of Pennsylvania it was clearly pointed out that the percentage of fixed carbon in the coals of that State increases from west to east, and also that the volatile matter decreases in the same direction. The result of this progressive change is that the coals on the eastern margin of the region are of much higher rank than are those on the western margin. White* has recently shown that the same progressive change is characteristic of the entire region, and he has drawn contours of equal percentage of fixed carbon showing the change. The well-known fact that the fields of semibituminous coal are limited to the eastern margin of the region accords with this progressive devolatilization of the coals toward the east. Even along this margin they are irregularly disposed, and White has shown that this irregularity is due to variation in the pressure exerted on the coal-bearing rocks at the time of the great movement which folded the rocks of the Appalachian region. As this thrust was transmitted through broken and folded rocks it acted irregularly; in places the movement was taken up by the folding and faulting of the rocks, and in other places the thrust was transmitted direct to the coal-bearing rocks, and materially affected the quality of the coal. As the coals are the softest rocks involved in the thrust, they were transformed according to the intensity of the pressure, the transformation being greatest along the east side of the region, where the thrust was most severe, and least along the west side, where the thrust was least. Two other elements that materially affect the quality of the coal of a field or region are the sulphur and the ash. The variations in the quantity of these substances are due to original differences in the condi-

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* White, David, "Some Relations in Origin Between Coal and Petroleum," *J. Washington Acad. Sci.*, **5**, pp. 189–212, **1915**.

tions that permitted mineral-bearing waters to circulate through the coal bed since it was formed. These conditions can not be determined, so the variations in composition due to these factors can not be foretold to any great extent.

During the deposition of the coal beds the Appalachian region. was doubtless a great swampy country near sea level, but even then it appears to have been in the form of a basin, whose deepest part was in western West Virginia. On account of this depression there was probably open water here, at least during part of the time when the coal beds were being deposited, for the coals are generally absent from this part of the region. These beds, if present, would be deeply buried, but their absence has been revealed by deep drilling done to find oil and gas.

Interior Province.—The Interior province includes all the bituminous coal fields and regions near the Great Lakes, in the Mississippi Valley, and in Texas. It is made up of four distinct regions—the northern region (Michigan); the eastern region (Illinois, Indiana, and western Kentucky); the western region (Iowa, Missouri, Kansas, Oklahoma, and Arkansas), and the southwestern region (Texas).

As these regions, with one exception, are not near mountainous uplifts, the coals are of low rank, for little pressure has been exerted upon them, and their change or devolatilization has been only such as resulted from the long-continued pressure of the overlying rocks. This statement is eminently true of the northern and eastern regions, the Iowa and Missouri portions of the western region, and the southwestern region; but as the southern part of the western region is near or a part of the mountainous area of uplifted rocks in Arkansas, the coal beds have been materially affected. They have been devolatilized to about the same extent that the Appalachian coals have been devolatilized by the great pressures that folded the rocks of the Appalachian Valley. The Ouachita disturbance changed the coal of Arkansas to semibituminous coal, or even to semianthracite, and the pressure has been effective as far west as a point about 50 miles within Oklahoma. Beyond this point the coal has not been converted into semibituminous coal but has been considerably altered, so that today it is regarded as superior to the coals of adjacent fields. The pressure also has devolatilized the coals farther north, in Kansas, changing them to coals of considerably higher rank than the coals of the region farther north. The coals of the northern part of this province have a large moisture content, which of course produces low heating value and a generally poor coal.

The northern and eastern regions are in the form of wide, generally shallow basins in the coal-bearing rocks, the deepest parts of which lie near their centers, toward which the beds dip lightly from the margins. The coal-bearing rocks in the western and southwestern regions do not lie in basins, or rather they constitute the eastern margin or rim of the greatest basin on the continent—the basin of the Great Plains. Throughout Iowa, Missouri, Kansas, Oklahoma, and Texas the coal-bearing rocks dip lightly westward and pass beneath the later rocks of the Great Plains. They emerge in the Rocky Mountains, on the west side of the Great Basin, but here the rocks of this age are not coal bearing, and no one knows where the change occurs from one to the other. The passing of the coal-bearing rocks under the cover of the later rocks of the Great Plains is shown on the map by the dotted pattern in the light tint. That part of the western region which lies in Arkansas is merely an eastern outlier in which the rocks are greatly folded, and in which the coals are therefore much devolatilized and improved in rank; but this area is still connected with the main region to the west.

Although the coal of the Interior province as a whole is not equal in quality to that of the Eastern province, it is very extensively mined and is used for heating and for generating power in the many cities and towns of the Mississippi Valley and the Great Lakes. In fact, the presence of these extensive coal fields in near proximity to the rich agricultural lands of this country and to the avenues of transportation—railroads, lakes, and rivers—has been largely instrumental in developing the great manufacturing centers of Chicago, St. Louis, and Kansas City and has been an important factor in the development of the railroad systems that gridiron this fertile country in all directions.

Gulf Province.—The Gulf province is at present of slight commercial importance. The coal is mostly lignite, and it has been mined at only a few localities in the State of Texas. The same kind of lignite occurs in Arkansas, Mississippi, and Alabama; but, owing to the presence of high-rank coal near by in the fields of Arkansas, western Kentucky, and Alabama, it has not been prospected except in a few areas. The lignite is contained in rocks of Eocene (early Tertiary) age, generally sandstone and clay, that are so soft as to make mining difficult and expensive.

The old idea that lignite is of recent formation and is of low rank because of that fact is generally true, but there are many exceptions. Some of the most valuable coal beds in the Western States are of the same age as the Texas lignite, yet they are of high rank. A study of the coal fields of the United States shows clearly that, although age is a factor in the alteration of coal, it is generally not the principal one. The controlling factor is the presence or absence of disturbances in the rocky crust of the earth, either in the coal field or close to it. Thus in the lignite fields of Alabama, Mississippi, Arkansas, and the northern part of Texas there have been no mountain-making disturbances since the lignite was formed. It may be said that the region is in its native condition; but near the Mexican border, in the vicinity of Laredo and Eagle Pass, the coal has been changed to a higher rank by the uplift of the Sierra Madre Oriental, of Mexico, which lies only a short distance to the southwest. Similarly, in Washington and in other States of the West the disturbances which have produced the mountains have so changed the coal that, instead of being lignite, it is now bituminous coal or even anthracite. The lignite of northern Texas and southern Arkansas is of better quality than that of the central part of Texas, the difference being due probably to the different conditions under which it was deposited. The lignite in the southern part of Texas seems to have been formed largely of trees and stems, which are clearly visible in the lignite today; but in the northern part of the State there appears to have been open water in which the accumulation of organic matter consisted mostly of spores, seeds, and spore cases that grew on the plants in the surrounding areas. Such wood as fell or drifted into the water decayed, for the most part, so that its resin contents fell to the bottom, there to mingle with the spores and other resistant detritus. The result is that this lignite is very rich in bituminous matter; it is subcannel coal or cannel coal in the process of formation. The rocks containing the lignite dip gently toward the Gulf and pass under younger rocks. These effectually conceal the Eocene rocks and the beds of lignite, but it does not seem probable that the lignite extends very far in this direction, for when the lignite was formed this area was a low coastal plain, which sloped gently to salt water, and as the swamps were limited to the land area they were probably not very wide.

Northern Great Plains Province.—The Northern Great Plains province includes all the coal fields in the Great Plains east of the Front Range of the Rocky Mountains. In this province the rocks generally lie flat or are but little disturbed, and in consequence the coals are of low rank, being either lignite or subbituminous, except in a few of the basins near the mountains, where the forces that caused the upheaval have locally changed the coal to higher rank. This progressive increase in rank toward the regions of mountain making is apparent in this province, as may be seen not only by comparing the coals of the different fields or basins, but by comparing many of the coals within a basin, region, or field.

The largest coal region in this province is the Fort Union region, lying in North Dakota, South Dakota, Montana, and Wyoming. The northeastern part of this region consists of a very broad, flat basin, in which the dips on the margin are so slight as to be perceptible only by the aid of a level. The southwestern extremity is more sharply folded, consisting of a rather broad, flat trough lying between the great upfold of the Bighorn Mountains on the west and the lower dome of the Black Hills on the east. Although the Fort Union region incloses the Black Hills in a great semicircle the coals there show little or no effect of that uplift, but they do show a decided change toward the Bighorn Mountains. Thus throughout North and South Dakota and northeastern Montana the coal is a brown woody lignite with a moisture content, as it comes out of the ground, of 40 to 45 per cent, but in the vicinity of Miles City, Mont., the brown lignite begins to lose its apparently woody structure and to take on the black color and the general appearance of a subbituminous coal. The change is, however, very gradual, and throughout a zone 15 or 20 miles in width can be seen the mingling of the two types; probably no two geologists would agree on the position of the line marking the place where one leaves off and the other begins. The subbituminous coal in southern Montana is of very poor quality, but farther southwest, in Wyoming, it improves until it reaches its best development in the vicinity of Sheridan, Wyo., where it has been mined extensively for a number of years. At this place the moisture content of the coal as it comes from the mine is only about 25 per cent, and for this reason alone its heating value is 30 per cent higher than that of the lignite of North Dakota.

Many of the coal beds in the Fort Union region are thick; those that are worked measuring from 3 to 40 feet. In almost every section of land that has been carefully examined there have been found a number of thick beds, so that the quantity of unmined coal or lignite in this region is very great.

The lignite and subbituminous coal of this region, as well as that of most of the other fields and regions of this province and of the Rocky Mountain province, ignite easily, and many of them have been burned along the outcrop. Some of the beds are now on fire and are objects of curiosity to those who are not familiar with the country. The heat generated by the burning has been in many places so intense as to partly fuse the overlying shale or sandstone, producing a peculiar, slag-like material of a deep-red color. In other places the heat has not been sufficient to melt the adjacent rock but has changed its color to a dull-red, resembling that of brick. Red hills and ridges, whose color is due to the burning of the coal, are common in the western fields and are considered indications of the former presence of coal beds. The depth to which burning extends depends on the depth of cover; for the coal can burn only to depths to which air is accessible, consequently burning is generally limited to a few hundred feet. This low-rank coal also ignites easily in mining, and many mines have had to be permanently abandoned because of fires.

There is very little mining in the Fort Union region, because the inhabitants are engaged chiefly in raising stock and farming, and there are no large towns or cities in which much manufacturing is carried on. The absence of manufacturing explains in part the lack of mining, but the greatest drawback to the establishment of mines is the poor quality of the lignite, which precludes its use *per se* as a fuel in many manufacturing processes. Although winter in this region is very severe and fuel is in great demand, those who have attempted to mine the lignite have found difficulty in marketing it in competition with high-rank Pennsylvania and West Virginia coal shipped over the Great Lakes and thence by rail to the lignite region. In the southwest end of the region, where the coal is of the subbituminous rank, the operators have been more successful in opening mines and in building up a large trade. The two centers of production are Sheridan and Glenrock, near Douglas, Wyo., and the coal mined around these centers finds a ready market, especially in the north, where better coal is difficult to obtain.

Although the coal in that part of the Fort Union region which surrounds the Black Hills shows little effect of the upheaval that formed the hills, the coal found immediately on the flanks of the uplift shows a decided improvement in quality as a result of the formation of the Black Hills. The region containing this high-rank coal is rather small and lies entirely on the west side of the uplift. The coal is contained in rocks of Lower Cretaceous age and corresponds with the coal mined at Sand Coulee, south of Great Falls, Mont. The principal center of development is at Cambria, north of Newcastle, Wyo. The coal is of bituminous rank and has been used largely in the manufacture of coke. The coal bed, however, has many partings of shale, and both the coal and coke therefore contain so high a percentage of ash that they can not easily compete with the lower-rank coals of adjacent regions.

Coal like that of the Sheridan district, though perhaps of somewhat better quality, is rather extensively mined in the Bull Mountain field, on Musselshell River. This field is comparatively new, its development dating from the building of the Pacific Coast extension of the Chicago, Milwaukee & St. Paul Railway, in 1908. The field is small, having an area of about 1,000 square miles, but it includes a number of beds, some of which attain considerable thickness. The coal is of the same geologic age as the lignite in the eastern part of Wyoming and in North Dakota, but here it has been changed to a high-rank subbituminous coal, about equal to the best subbituminous coal of the Northern Great Plains and Rocky Mountain provinces.

In the Milk River valley and along Missouri River south of the Bearpaw Mountains there is considerable coal, but the beds are generally thin or are only locally expanded into beds thick enough to be of present commercial value. Another obstacle to the development of these fields is the deep cover of glacial drift, which, north of Missouri River, makes the tracing of coal beds and their exploitation very uncertain. The coal is generally subbituminous, but in places it is of the bituminous rank.

The highest-rank coal in this part of the province is that in the Great Falls and Lewistown fields, of Cascade and Fergus counties, Mont. This coal is bituminous and for a number of years was mined and coked at Belt to supply the copper smelters at Anaconda. The coking coal is limited, however, to this locality, and the manufacture of coke from it was discontinued several years ago. The coal contains a large percentage of impurities and has therefore not met with as ready a sale as was expected when the mines were first opened. The coal is mined somewhat extensively for steaming and domestic use in the region round about the mines.

Farther south, in Colorado, the next field of consequence is generally known as the Denver region. This region extends from the Wyoming line southward as far as Colorado Springs. The coal is extensively mined northwest of Denver and to some extent at Colorado Springs. It is subbituminous and finds a ready market in and about Denver and Colorado Springs as a domestic fuel. The coal northwest of Denver is mined along the upturned edge of the coal-bearing rocks at the foot of the mountains, and here it is a fairly good coal of its class; but that at the southern end of the region appears not to have been so greatly affected by the uplift of the mountains and is consequently of much lower rank.

The Canon City field is a small basin of coal-bearing rocks in the great reentrant of the mountain front at Canon City. Owing to its proximity to the mountain uplift the coal has been changed to the bituminous rank, but it carries so high a percentage of ash that its sale in competition with cleaner coals is difficult, especially for domestic use. In the early days of railroad building in Colorado (about 1878) there was keen rivalry between the Denver & Rio Grande and Santa Fe railroads for the possession of this field as a source of locomotive fuel; but although both roads gained access to it the coal has been somewhat disappointing, because of its heavy ash content. Many mines have been opened, and the coal reaches a large market along the mountain front.

The Raton Mesa region, in the southern part of Colorado and the northern part of New Mexico, contains the most valuabe and highest-rank coal in this province. The Colorado portion is generally known as the Trinidad field and the New Mexico portion as the Raton field. The rocks lie in a basin-shaped structure, but the edge next to the mountain is sharply upturned and broken through by the old volcanic stock and dikes of the Spanish Peaks. As this basin is filled with younger rocks to a depth of at least 7,000 feet the coal-bearing rocks are deeply covered, and mining has been limited largely to the eastern margin of the region. By the great stresses produced in the folding of the rocks, and possibly by the heat evolved from the stocks and dikes of igneous rocks, the coal has been so much altered as to become of higher rank than any other coal found in this province, except possibly that of the Black Hills. The coal in the southern part of the region makes excellent coke, and the product of the ovens supplies most of the smelters in the Rocky Mountain province.

Rocky Mountain Province.—Until within a few years the coal resources of the Rocky Mountain coal province were largely unknown except a few areas of high-rank coal in Colorado and neighboring States, which were exploited by some of the large steel companies or railroad corporations. Since 1905 the United States Geological Survey has examined most of these fields, either in reconnaissance or in detail, and now the fields of this province are almost as well known as those of the Eastern or Interior provinces.

The coal-bearing formations of the Rocky Mountain province are of Cretaceous and Tertiary (Eocene) age, and doubtless originally extended in almost unbroken sheets throughout the province. Since the deposition of the earliest of these beds the province has been greatly disturbed by movements in the crust of the earth, which resulted in the formation of great mountain ranges. The areas between the ranges were either depressed or remained stationary while the movement was in progress, so that great intermontane basins or depressions lie in the mountainous region. Most of these basins are floored with coal-bearing rocks of either Cretaceous or Tertiary age or are underlain by such rocks at a greater or less depth. In many basins the coal is not so deep but that it may in the future be reached by deep shafts; but in a few it lies so deep that it probably can never be mined.

The Rocky Mountain province contains a greater variety of coal than any other province in the United States. The coal ranges from lignite to anthracite and includes all the ranks described in this chapter, though the prevailing ranks are sub-bituminous and low-grade bituminous. The coal is mined rather extensively, the greatest centers of development being Red Lodge, Mont.; Rock Springs and Kemmerer, Wyo.; Crested Butte and Durango, Colo.; Castlegate and Sunnyside, Utah; and Gallup, N. M.

In Montana the coal fields of the Rocky Mountain province are neither large in area nor of great commercial importance. Persistent efforts have been made to develop the fields that contain the best coal, especially in the vicinity of Livingston at Trail Creek, Chestnut, and Electric; but for various reasons mining has not been successful, and the only mine now in operation is a small one in the Trail Creek field. The coal in these fields is bituminous and has not been coked near Livingston and Electric, but the beds are thin and greatly disturbed, and the coal is too dirty to compete with other coals in the market.

Many of the areas are small basins in lake beds in the mountain valleys, which contain in places thin beds of lignite. These are probably of Miocene (later Tertiary) age.

The most important area in this part of the State is the Red Lodge field, which, so far as Montana is concerned, might be considered in the Northern Great Plains province, because it lies east of the Front Range of the Rocky Mountains, but it is also the northern continuation of the Bighorn Basin region of Wyoming, which lies west of the Bighorn Mountains, a range that is generally considered the easternmost range of the Rockies, and for that reason the Red Lodge field is here treated as a part of the Rocky Mountain coal province. The coal of the Bighorn Basin is mostly subbituminous, but that in the lower coal-bearing formation, at the north end of the basin, in the vicinity of Bridger, Mont., is bituminous. The subbituminous coal, however, is of excellent quality, especially that mined at Red Lodge and Bear Creek, at the north end of the basin, and at Gebo, near the south end, and compares favorably with the best subbituminous coal of the Rocky Mountain province.

The coal-bearing rocks outcrop in a narrow belt about the great basin and near the foot hills of the surrounding mountains. They dip toward the center of the basin, where, as is indicated on the map, they are deeply covered with other rocks that were deposited later. It is estimated that the coal beds near the center of the basin may lie as much as 10,000 ft. below the surface. The irregularity in the thickness of the coal beds and the fact that few railroads have been built within the basin have led to the development of only two mining centers, one at Red Lodge, Mont., in the north end of the basin, and the other at Gebo, Wyo., in the south end of the basin.

The Wind River Basin is of much the same character as the

Bighorn Basin, except that the late Tertiary formations more nearly conceal the coal-bearing rocks. For this reason less is known regarding the coal beds, which have been mined in only a small way. The coal is subbituminous and compares favorably with the coal of the same rank in adjacent fields. A little coal has been mined in the vicinity of Hudson. The coal in the middle of the basin lies under thick cover and is probably too deep to be profitably mined.

The Green River region is a great irregular basin in southwestern Wyoming in which the Rock Springs dome rises like an island in the sea. This region contains, besides the Green River Basin proper, a basin lying between Rock Springs and Rawlins, which extends southward and terminates in a point near Steamboat Springs, Colo. The rocks of this basin include four coal-bearing formations, which are generally well exposed in the upturned rim and in the Rock Springs dome, near the center of the basin. Several kinds of coal occur in the basin ranging in rank from subbituminous to anthracite. The Tertiary rocks contain subbituminous coal, the Cretaceous rocks subbituminous and bituminous coals, and where these have come in contact with igneous sills, as they have northwest of Steamboat Springs, Colo., anthracite has been formed. The coal at Rock Springs, Wyo., may be regarded as the best type of bituminous coal in this region, and coal of about the same quality occurs along Little Snake River, in Wyoming, and also in the valley of Yampa River, between Hayden and Steamboat Springs, Colo. In the Green River Basin the coal beds are so deeply buried by later formations that it is doubtful whether they can ever be mined. The principal mines are in and about Rock Springs, Wyo., and in the valley of Yampa River below Steamboat springs, Colo.

This enormous basin, which extends from Rawlins on the east to and beyond Grainger on the west, and from the Wind River Mountains on the north to Yampa River on the south, is one of the largest and most important coal regions in the Rocky Mountain province. It embraces an area of about 17,000 square miles and contains four coal-bearing formations, each of which carries from 4 to 20 coal beds, ranging in thickness from 2 ft. to 20 or 25 ft. It is true that the coal in many areas of this region lies so deep that it may never be worked; but after excluding all such areas it is estimated that at least

6,000 square miles is underlain by coal beds that can be mined when the demand for fuel is sufficient to warrant the expenditure necessary for sinking deep shafts. The quantity of coal in the ground in this region is enormous, probably exceeding that in any other region of similar area in this country. There are only two centers of mining in the Green River region. The most important is Rock Springs, Wyo., on the Union Pacific Railroad, where mining has been carried on since that road was completed in 1869. The other mining center has recently developed in the vicinity of Steamboat Springs, Colo., on the Denver & Salt Lake Railroad ("Moffat road").

West of the Green River Basin is the Hams Fork coal region, which consists of a number of folds of coal-bearing rocks. These extend nearly northward from the southwest corner of Wyoming for a distance of 200 miles. The coal is high-rank bituminous and subbituminous. The coal beds vary considerably in thickness, the largest one of subbituminous rank measuring at one place 84 ft. of clear coal. This is the thickest coal bed that has been mined or prospected at the surface in the United States. Somewhat thicker beds have been reported in drill logs in other regions, but the uncertainty of determining the thickness and character of beds penetrated by a churn drill renders such a report of doubtful value. The greatest center of mining is at Kemmerer, Wyo., and this coal is regarded as the best that is produced in the State.

East of the Green River Basin is the Hanna field or basin. This basin lies just back of Laramie Mountain, or the Front Range, and is named for Hanna, Wyo., the principal town and the center of the mining industry. The coals are of low rank, being generally subbituminous but possibly including some bituminous coal that is not yet developed. The character of the coal probably explains the meagerness of the mining operations in this field, as the coal can not hold its own, except for local uses, in competition with the better fuel of Rock Springs, on the west, or some of the Colorado coals, on the south.

South of the Uinta Mountains lies a great, irregular basin-shaped coal region, which is called the Uinta region. It extends eastward and southward from the Wasatch Plateau and terminates in a spoon-shaped point near Crested Butte, Colo. The coal-bearing rocks form the rim of this great troughlike depression. From the rim they dip toward the middle and are there deeply buried by later formations. The coal varies considerably in quality, being best at the two extremities of the region. The coals in the vicinity of Crested Butte have been greatly altered, partly by the mountain-building forces and partly by the volcanic material that has been poured out in this area, and as a consequence some of the coal is high-grade anthracite and some belongs to lower ranks. On the rim, especially to the north, the coal changes within a short distance to subbituminous, and this rank characterizes the coal along the north rim. The coal on the south rim is generally bituminous, and west of Green River it improves rapidly in quality and increases in quantity to Castlegate, Utah, where there are many beds of high-grade bituminous coal.

The coal beds of the Uinta Basin are not so numerous nor so extensive as those of the Green River Basin, to the north, but even this basin contains an enormous quantity of coal. The area of the basin is about 16,500 square miles, a little less than the area of the Green River Basin, and the part in which the coals are accessible for mining is about 5,750 square miles. The coal beds are most numerous at the two extremities of the region, and naturally those parts contain the greatest quantity of coal. At Newcastle, on Grand River, 109 ft. of coal in workable beds has been measured, and the beds at the western extremity are probably just as thick. The thickest bed reported is 40 ft., but beds that measure from 6 to 15 ft. are fairly common. The center of mining in the western part of the basin is Castlegate, Utah, where the coal is of excellent quality, and some of it is being coked for use in smelters. The centers of mining in the eastern part of the basin are Crested Butte, where both bituminous coal and anthracite are mined extensively, and Newcastle, on Grand River, a few miles below Glenwood Springs. The coal at Newcastle is generally subbituminous, but a short distance to the south it changes to bituminous and some of it is coked.

The coal-bearing rocks at the west end of the Uinta Basin turn to the south in the Wasatch Plateau, and for convenience of discussion this area is treated as a separate field. The same coal beds that occur in the vicinity of Castlegate, in the Book Cliffs, are found in the cliffs that form the eastern front of the Wasatch Plateau, and the coal is of about the same rank and thickness. The coal beds in the high cliffs that form the east front of the Wasatch Plateau are nearly horizontal and are well exposed in every canyon that cuts this rim. The plateau has a width of about 25 miles, but the coal beds are not exposed along its western margin, because the rocks on that side dip to the west and pass below later formations.

Most of the coal of this field occurs in the Mesaverde formation, but some is found near the base of the Mancos shale. Coal is not generally found in this shale in the Rocky Mountain province, but toward the southwest this lower coal-bearing formation becomes more and more important, and in the next fields to the south it is the principal source of supply.

The Colob and Kaiparowits plateau fields lie at the south end of the Wasatch Plateau, near the south line of Utah. The coals of the Colob Plateau have been examined in considerable detail, but those of the Kaiparowits Plateau are known only from casual inspection and from reports of persons who have traveled through that remote region. The coal of the Colob Plateau occurs near the base of the Mancos shale and is of bituminous rank. It lies high on the plateau and is therefore accessible with considerable difficulty. Its disadvantageous position has not, however, prevented its development, but it has been mined only to supply local needs. A small outlier of the field in Iron County, west of Cedar City, contains anthracite, but the coal is dirty and probably can not compete with the lower-rank but cleaner coals of the Colob Plateau.

The coal in the lower part of the Mancos shale is reported to occur in fairly thick beds in the vicinity of Paria, but no examination has been made to determine their quality or extent. In the Kaiparowits Plateau, northeast of Paria, beds of coal 12 or 15 ft. thick have been opened in the face of the cliff and coal has been mined for local use. This coal is in the Mesaverde formation, which probably extends unbroken from the Wasatch Plateau on the north, but in the intervening area it is so covered with lava that the actual connection has never been traced. The quality of this coal has not been determined, but it is probably bituminous and of about the same rank as that in the plateau farther north.

The San Juan River region lies south of the San Juan Mountains, partly in Colorado and partly in New Mexico. It is a great basin-shaped depression with a prolongation running southward through the town of Gallup, on the Santa Fe Railway. Two coal-bearing formations are involved in the folding that produced the basin—the Mesaverde formation at the base and a part of the so-called ''Laramie'' which has recently been named the Fruitland formation* at the top. Both formations are of Upper Cretaceous age; the lower one underlies the entire basin, but the upper is restricted to the part of the basin that lies north and east of Chaco River. The depth of the coal-bearing rocks in the center of the basin has not been determined but is probably several thousand feet. The rocks on the rim of the basin dip toward the center; in the northern part the dip is rather steep, but in the southern part it is so gentle that it can scarcely be detected by the unaided eye.

The coal in the lower formation is generally of better quality than that in the upper formation, but each has felt the effects of the movements that resulted in the upheaval of the San Juan Mountains. The coal is normally subbituminous, but around the north rim the lower coal has been changed by the pressure into bituminous coal that in places is good enough to coke. The upper coal is less altered, but toward the east it also is changed to bituminous coal. South of San Juan River all the coal in both formations is subbituminous except possibly some on the east rim, which has been affected by the uplift of the Nacimiento Mountains. The coal beds of the Mesaverde formation range from 3 to 6 ft. or more in thickness wherever they have been mined or prospected, and they are exposed at the surface throughout a wide expanse of country, extending from the rim of the basin north of the Santa Fe Railway on the south to Chaco River on the north and across the entire width of the basin in the other direction. The coal beds of the Fruitland formation, although they contain coal of lower rank, are thicker, especially in the northern part of the basin, where they have a known maximum thickness of 40 ft. Such a bed is exposed in the banks of Animas River below Durango, Colo., but the bed is badly broken by partings which would make mining expensive .and detract greatly from the value of the coal.

The north and south sides of the basin have railroad con-

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* BAUER, C. M., Contributions to the Geology and Paleontology of San Juan County, N. M.—1, Stratigraphy of a Part of the Chaco River Valley, *U. S. Geol. Survey Prof. Paper* **98,** p. 274, **1916.**

nection, and in these parts the coal is mined, but the mines on the north side are handicapped by having to ship their coal over two mountain ranges and those on the south side have to handle a low-rank fuel, which can not easily compete with coal of a higher rank in near-by fields. Despite these drawbacks and the keen competition of fuel oil, the mines have managed to keep in operation, and the coal meets with a ready though local sale.

The Black Mesa field of Arizona is entirely undeveloped and is therefore largely unknown, except locally. It lies in the Hopi and Navajo Indian reservations and is about 75 miles distant from the nearest railroad point. The coal beds are in the Mancos shale and the Mesaverde formation, both of Upper Cretaceous age. The rocks lie in the shape of a broad, flat basin, forming a plateau upon which some of the Hopi Indian villages are built. The coal is subbituminous but of excellent quality and is used locally for the Indian schools.

Besides the main fields and regions noted above, there are a number of isolated outliers of coal-bearing rocks, mainly in New Mexico and Arizona, that are too small and unimportant to be considered here individually. Some of them, like Los Cerrillos, Carthage, and Capitan, in New Mexico, have been developed to some extent, because they contain coal of a better quality than could be found in many of the larger regions. Thus Los Cerrillos has for many years produced a fine grade of anthracite from a coal bed that has been locally changed by the heat of a sill of igneous rock, and the Carthage field has yielded coking coal. Most of these small fields are comparatively insignificant and will not be described further.

Pacific Coast Province.—The coal in the Pacific Coast province is limited largely to the State of Washington. Both California and Oregon have small fields within their borders, but the coal is generally of low rank or poor quality, and but little mining has been attempted. Washington, on the other hand, is fairly well supplied with coal in the western part, where it is most needed for the various industries that have been developed about Puget Sound. The coal-bearing rocks of Washington have been so greatly folded and contorted and then so deeply covered with glacial drift that it is possible to separate only a few of them into well-marked fields, and according to the local practice they are therefore generally subdivided arbitrarily according to the county in which they occur. The local practice will be followed here.

The coal fields of King County lie on the west side of the Cascade Mountains, extending from tidewater in the vicinity of Renton, 12 miles southeast of Seattle, to the foot of the mountains on the east. The thick cover of glacial drift and the almost impenetrable forest make coal prospecting laborious and difficult except near the principal streams, where these obstructions have been to some extent removed. The coal-bearing rocks are of Eocene (Tertiary) age and correspond in time of deposition with the lignite of the Dakotas, Montana, and Texas. In Washington, however, mountain-building forces have been so active in late Tertiary time that many of the coals have been changed from lignite to subbituminous, bituminous, and even to anthracite. In general, the coals nearest the Cascade Mountains are the most altered. The mountain-building forces not only changed the character of the coal but also folded and broke the rocks in a most intricate manner, so that in places mining is difficult and expensive. The coal beds generally dip at considerable angles and are locally broken and displaced, so that it is difficult to follow a coal bed in mining. The old swamps in which the coal was deposited were apparently subject to many floods, which washed mud and sand in from the surrounding higher lands. These materials settled to the bottom of the swamp, forming a shale or sandstone layer or parting in the coal bed, which today detracts greatly from its value, for the shale or sandstone must be removed before the coal can be marketed, and its removal is generally difficult and expensive. If the coal is put on the market after it is simply screened, it will contain a large percentage of ash, which makes it difficult to sell. The lump coal is generally so treated and reaches the market in fairly good condition, but in many places the fine coal is too dirty for marketing and must be washed before it can find purchasers. All coals contain more or less foreign material, in the form of partings or binders, but the coal of Washington includes more of such partings than the coals of many other parts of the United States.

The coals of King County are of subbituminous and bituminous rank in about equal proportions. The best coal in the county, to judge from the heating value of the pure coal, occurs along the mountain front from Snoqualmie on the north to Cumberland, a little south of Palmer Junction, on the south, embracing a belt of country not more than 3 or 4 miles in width. West of this belt lies a similar belt of good coal, which, however, has a lower heating value than that of the belt just mentioned; and then west of all is a belt of indefinite width in which the coal is subbituminous.

Many large mines are developed in this county, especially in the higher-rank coals near the mountain front, but some of the subbituminous coals, owing largely to their position on or near tidewater, are extensively mined, the coal finding a ready market as a domestic fuel.

The coals of Pierce County are the best in the State, but the known productive territory is very much smaller than that in King County. All the coals of this county so far mined or prospected are of bituminous or higher rank. The coal districts may roughly be divided into two groups—(1) the Wilkeson-Carbon Hill and adjacent districts, containing mainly high-grade bituminous coal but also some semibituminous coal, much of which will coke; and (2) the Melmont, Fairfax, and Montezuma districts, containing coal having a fuel ratio ranging from 2½ to more than 6. Thus most of these coals come within the rank of high-class bituminous and semibituminous coal. The coal at Wilkeson is the only coal in the State that has been extensively coked. All these coals bear an excellent reputation in the market.

The coal-bearing rocks in the fields of Pierce County are even more strongly folded and faulted than those of King County, on the north. Many of the coal beds are cut by dikes that ray out from the great volcanic center of Mount Rainier. The coal beds are exposed mainly in the deep canyons cut by Carbon River and its tributaries and consequently have been mined mainly along that stream. The mines are only a short distance from tidewater at Tacoma, with which they are connected by a branch line of the Northern Pacific Railway that was long ago built into this field for the purpose of obtaining fuel for use in locomotives.

All the developed coal of Kittitas County is in the Roslyn field, which is a regular, shallow basin in the vicinity of Cle Elum, in the valley of Yakima River, on the east side of the Cascade Mountains. The basin is not complicated by minor folds and faults, as are those on the west side of the mountains, and hence mining conditions are almost ideal. The coal is a hard, blocky coal of fairly uniform quality, well adapted to shipping and handling. It has been extensively used by the Northern Pacific Railway for locomotive fuel. It is mined by slopes and drifts on the outcrop and by shafts in the middle of the basin.

The coal fields of Thurston and Lewis counties are neither so well known nor so well developed as those of the countries just mentioned, largely because the coal of better rank near the mountains is in many places deeply covered with lava flows, glacial drift, and almost impenetrable forests. The coal in this region near the mountains is of high rank, in many places anthracite, but the complicated folds into which the strata have been bent and the abundance of partings in the coal beds make it impossible to mine the coal at a profit. The developed fields in these counties lie farther from the mountains, along the railroad lines leading from Tacoma, Wash., to Portland, Ore. The coal beds in this part of the region are comparatively undisturbed and lie in an almost horizontal position. The coal, not having been subjected to the pressures that were exerted farther east when the mountains were uplifted, is of low rank. Those who have examined it most carefully are undecided whether to class it as lignite or subbituminous coal. It lies close to the dividing line between those two ranks and has generally been classed as subbituminous. It contains a large percentage of moisture, slacks badly when exposed to the atmosphere, and is little if any better as a fuel than Texas lignite. The extent of this low-rank coal has not been accurately determined, but it probably extends southward to Columbia River.

The coal fields of Whatcom and Skagit counties are perhaps less extensive than those of the counties so far considered. The coals in these counties range in rank from subbituminous coal at Bellingham to anthracite at Glacier. The anthracite lies in the valley of Glacier Creek northwest of Mount Baker and compares favorably in quality with some of the anthracite of the East. It has not yet been produced on a commercial scale, but mines are being opened, and it may soon be put on the market. High-rank coal has been mined and coked at Blue Canyon, in Whatcom County, and at Cokedale, in Skagit County, but these plants are now abandoned. The oldest mining operation in this region was at Bellingham, where a bed of subbituminous coal 14 ft. thick was mined extensively about 30 years ago. On account of the low rank of the coal, the mine was soon abandoned, and now very little coal is mined in either Whatcom County or Skagit County. The rank of the coal, like that of all other coals in this country, decreases away from the mountains.

There are a number of small fields or isolated occurrences of coal in other counties, but they are of little importance and will not be described here.

Only a little coal occurs in Oregon, and that is of poor quality. Mining has been done in a commercial way in the Coos Bay field, on the coast, on the southern part of the State. The coal in this field is subbituminous and has done little more than to supply the small local demand. Although there is considerable coal in this field, it is difficult to mine, and much of it lies below the waters of the bay. The field is not promising and probably never will be a large producer.

The best coal so far discovered in Oregon is in the Eden Ridge field, in the southern part of Coos County. The rocks are somewhat more disturbed here than in the vicinity of Coos Bay and the coal is of higher rank. It is bituminous, and some of it will coke, but the beds are full of shale partings, which make the coal very dirty. The field has no railroad connection at the present time, and consequently no mining has been undertaken.

Coal has been noted near Medford, in Jackson County; in the Nehalem Valley, in Columbia County, and in other parts of the State, but at none of these places is it of sufficient thickness or purity to be of value.

California, although rich in many other mineral resources, is singularly deficient in coal. At present the lack of coal is not felt, for the State has abundant supplies of fuel oil, but these supplies will sooner or later be consumed, and when the oil is exhausted the problem of obtaining coal will become vital. The only coal field of any prospective importance is that which lies in the Coast Ranges, in San Benito and Monterey counties, and which is known from the places at which the coal has been prospected. The most ambitious attempt to develop this field was made at Stone Canyon, Monterey County, where a bed of coal ranging from 10 to 14 ft. in thickness was opened. The attempt was unsuccessful, however, and the mine was abandoned. This coal is of the bituminous rank, and is the only coal of this rank in the State. It is very rich in bituminous matter and is in composition a cannel coal, though it has none of the physical properties of such a coal.

ANALYSES OF REPRESENTATIVE COALS*

In order that the reader may obtain an idea of the comparative value and rank of the coals of the United States, analyses

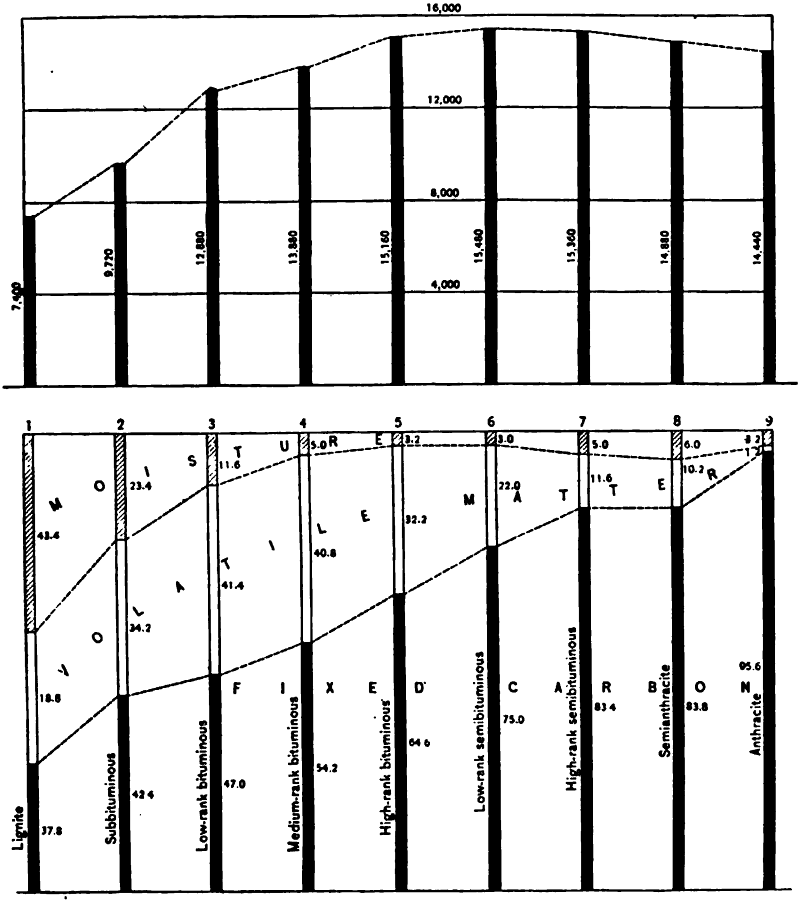

FIG. 1.—Diagrams showing the chemical composition and heat efficiency of the several ranks of coal. Upper diagram: Comparative heat value of the samples of coal represented in the lower diagram, computed on the ash-free basis. Lower diagram: Variation in the fixed carbon, volatile matter, and moisture of coals of different ranks, from lignite to anthracite, computed on samples as received, on the ash-free basis.

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*Standard methods for the analysis of coal are given on pages 1214–30.

of representative samples are tabulated on the following pages. The figures given are those obtained by the analysis of individual samples of coal, but each sample has been so selected that it represents the average composition of the coal of a certain district or field or the composition of a certain rank of coal.

Most of the analyses given in the table were made by the Bureau of Mines or the United States Geological Survey and so are strictly comparable, but for a few coals, as indicated, such analyses are not available and the figures given are taken from a State report.

The analysis given is that of the sample of coal as it was received at the laboratory. This sample was sealed in an air-tight receptacle immediately after it was cut in the mine, and it reached the laboratory in the same condition as it was in when it was cut in the mine. For this reason the analyses show a larger percentage of moisture than most analyses made for private persons, because the samples so analyzed have not been sealed and the coal has therefore lost some of the moisture it contained when it was in the mine. The Government analyses represent the coal as it leaves the mine and approximately as it reaches the consumer. If the coal is shipped in dry and hot weather some of its moisture may be evaporated; on the other hand, if rain falls on the coal in transit its original moisture content may be appreciably increased.

The analyses are as follows:

TABLE I.—ANALYSES OF REPRESENTATIVE COALS OF THE UNITED STATES (Unless otherwise specified all analyses were made by the United States Geological Survey or the Bureau of Mines)

Location and rank of coal	Moisture	Volatile matter	Fixed carbon	Ash	Sulphur	Heat value (B.t.u.)
Alabama						
Lookout Mountain, semibituminous	3.8	19.0	64.4	12.8	1.5	12,980
Blount County, bituminous	3.4	27.7	55.9	13.0	1.2	12,740
Birmingham district, bituminous, coking	2.4	25.9	66.8	4.9	1.5	14,490
Do	2.3	29.7	58.0	10.0	0.8	13,490
Birmingham district, bituminous	2.6	31.8	62.9	2.7	0.8	14,630
Carbon Hill district, bituminous	4.7	31.8	53.3	10.2	1.3	12,600
Tuscaloosa district, bituminous	1.6	25.0	68.5	4.9	0.5	14,700
Cahaba field, bituminous	3.1	35.0	55.8	6.1	0.4	13,560
Do	3.2	31.0	59.6	6.2	1.2	14,140

TABLE I.—ANALYSES OF REPRESENTATIVE COALS OF THE UNITED STATES—*Continued*

Location and rank of coal	Moisture	Volatile matter	Fixed carbon	Ash	Sulphur	Heat value (B.t.u.)
Arizona						
Black Mesa field, subbituminous	9.9	32.6	46.9	10.6	1.1	10,800
Arkansas						
Russellville district, semianthracite	2.1	9.8	78.8	9.3	1.7	13,700
Spadra district, semianthracite	1.7	10.5	79.5	8.3	2.5	13,870
Coal Hill district, semibituminous	1.4	14.8	76.9	6.9	1.5	14,330
Paris district, semibituminous	2.8	14.7	73.4	9.1	2.8	13,770
Jenny Lind district, semibituminous	1.6	17.4	73.1	7.9	1.4	14,160
Huntington district, semibituminous	3.5	16.7	72.0	7.8	1.3	14,020
Camden district, lignite	39.4	26.5	24.4	9.7	0.5	6,360
California						
Stone Canyon district, bituminous	7.0	46.7	40.1	6.2	4.2	12,450
Mount Diablo district, subbituminous	15.0	38.4	34.5	12.1	5.6	9,240
Tesla district, subbituminous	18.0	39.2	26.4	16.4	3.1	8,110
Colorado						
Denver field, subbituminous	18.8	30.5	44.5	6.2	0.3	9,650
Do	25.6	28.0	41.1	5.3	0.4	9,180
Colorado Springs field, subbituminous	26.2	29.7	37.7	6.4	0.3	8,350
Canon City field, bituminous	9.1	35.7	48.0	7.2	0.9	11,700
Trinidad field, bituminous, coking	2.3	29.8	58.7	9.2	0.5	13,780
Trinidad field, bituminous, noncoking	7.8	38.5	44.8	8.9	0.5	11,540
North Park field, subbituminous	20.0	32.5	42.5	5.0	0.6	9,750
Yampa field, anthracite	7.0	3.4	75.6	14.0	0.6	11,740
Yampa field, bituminous	10.4	37.9	45.5	6.2	0.4	11,470
Newcastle field, bituminous	7.1	40.8	46.9	5.2	0.5	12,620
Newcastle field, bituminous, coking	2.9	33.3	56.7	7.1	0.5	13,720
Coal Basin field, semibituminous	2.4	19.4	70.8	7.4	0.5	14,380
Crested Butte field, anthracite	3.0	2.9	86.6	7.5	0.7	13,500
Crested Butte field, bituminous	5.6	37.6	47.6	9.2	0.4	12,430
Grand Junction field, bituminous	7.6	33.6	52.9	5.9	0.7	12,440
Durango field, bituminous, coking	2.7	36.1	54.5	6.7	0.5	13,910
Georgia						
Manlo district, semibituminous	2.9	17.1	72.2	7.8	0.7	14,200
Idaho						
St. Anthony field, bituminous	11.5	37.2	47.0	4.3	0.5	12,090
Goose Creek field, lignite	34.3	26.6	25.7	13.4	2.5	8,610
Illinois						
La Salle County, bituminous	13.9	37.3	38.5	10.3	3.4	10,990
Peoria County, bituminous	15.5	34.7	39.8	10.0	2.9	10,740
Fulton County, bituminous	15.7	31.4	43.1	9.8	3.0	10,620
McLean County, bituminous	10.2	35.9	40.1	13.8	2.8	11,150
Logan County, bituminous	14.8	32.9	39.7	12.6	4.0	10,410
Sangamon County, bituminous	14.3	37.2	40.3	8.2	4.4	11,010
Macoupin County, bituminous	13.3	37.1	40.7	8.9	4.1	11,160
Montgomery County, bituminous	12.7	35.5	40.2	11.6	4.2	10,670
Madison and St. Clair counties, bituminous	12.7	36.4	41.4	9.5	3.7	10,990
Marion County, bituminous	10.3	37.4	39.8	12.5	3.7	11,080
Franklin County, bituminous	9.2	33.8	48.6	8.4	0.9	11,930
Williamson County, bituminous	8.8	29.9	53.8	7.5	1.1	12,220
Saline County, bituminous	6.0	32.4	54.3	7.3	1.7	12,790
Gallatin County, bituminous	3.4	35.2	52.5	8.9	2.9	13,190
Indiana						
Vermilion County, bituminous	10.5	39.5	39.6	10.4	4.0	11,430
Clay County, bituminous, block	15.4	32.6	46.1	5.9	2.0	11,680
Sullivan County, bituminous	13.6	35.0	44.6	6.8	1.1	11,550

TABLE I.—ANALYSES OF REPRESENTATIVE COALS OF THE UNITED STATES—*Continued*

Location and rank of coal	Moisture	Volatile matter	Fixed carbon	Ash	Sulphur	Heat value (B.t.u.)
Indiana—Continued						
Knox County, bituminous	10.6	38.1	43.0	8.3	3.7	11,750
Pike County, bituminous	11.3	38.3	43.5	6.9	3.1	11,920
Warrick County, bituminous	10.4	39.2	42.0	8.4	3.5	11,820
Vandenburgh County, bituminous	9.7	35.6	44.5	10.2	2.9	11,440
Iowa						
Boone County, bituminous[a]	19.5	33.4	38.3	8.8	5.4	10,520
Polk County, bituminous	14.4	37.8	36.8	11.0	5.9	10,640
Jasper County, bituminous[a]	9.3	39.2	39.1	12.4	2.4	11,210
Marion County, bituminous	15.7	36.9	35.8	11.6	5.1	10,290
Mahaska County, bituminous[a]	14.6	36.3	40.5	8.6	2.9	11,000
Lucas County, bituminous	18.7	31.8	41.8	7.7	2.4	10,510
Monroe County, bituminous	15.8	36.9	37.9	9.4	4.7	12,900
Wapello County, bituminous	11.3	38.7	39.5	10.5	4.7	11,350
Taylor County, bituminous[a]	20.2	30.1	38.3	11.4	4.2	10,120
Appanoose County, bituminous	17.1	35.4	40.4	7.1	4.0	10,930
Kansas						
Leavenworth County, bituminous	12.0	35.2	39.1	13.7	4.4	10,720
Linn County, bituminous	11.1	28.8	47.5	12.6	2.4	11,220
Crawford County, bituminous	4.9	33.5	52.5	9.1	5.0	12,940
Cherokee County, bituminous	5.1	32.6	53.4	8.9	4.3	12,930
Eastern Kentucky						
Johnson County, bituminous	6.4	36.2	54.1	3.3	1.2	13,460
Johnson County, bituminous, cannel	2.2	50.6	36.7	10.5	1.0	13,750
Pike County, bituminous	2.8	36.2	56.7	4.3	1.4	14,180
Letcher County, bituminous	2.5	36.5	57.0	4.0	0.6	14,150
Perry County, bituminous	3.9	37.2	54.8	4.1	0.8	13,730
Laurel County, bituminous	4.5	39.9	50.8	4.8	2.3	13,510
Harlan County, bituminous	4.4	35.0	56.9	3.7	0.7	13,920
Bell County, bituminous	2.8	37.8	56.3	3.1	1.0	14,240
Knox County, bituminous	4.2	36.4	53.3	6.1	0.8	13,410
Western Kentucky						
Daviess County, bituminous	11.8	36.8	42.0	9.4	3.3	11,150
Ohio County, bituminous	10.0	36.5	44.9	8.6	2.6	11,770
Muhlenberg County, bituminous	8.8	36.2	46.4	8.6	3.6	11,900
Hopkins County, bituminous	8.5	38.0	46.4	7.1	3.5	12,340
Union County, bituminous	3.9	37.1	49.7	9.3	3.5	12,830
Maryland[b]						
Georges Creek basin, semibituminous, high rank	0.6	16.6	72.1	10.7	1.3	13,380
Georges Creek basin, semibituminous, medium rank	0.6	17.7	73.0	8.7	1.4	14,010
Georges Creek basin, semibituminous, low rank	0.7	20.3	70.0	9.0	1.4	14,010
Upper Potomac basin, semibituminous	0.9	18.1	71.9	9.1	1.7	14,010
Upper Potomac basin, semibituminous	1.7	19.0	68.1	11.2	1.6	13,450
Castleman basin, semibituminous	2.1	22.0	67.1	8.8	2.3	13,870
Castleman basin, bituminous	0.7	24.0	66.8	8.5	1.4	13,970
Upper Youghiogheny basin, bituminous	1.2	23.0	63.9	11.9	2.1	13,260
Lower Youghiogheny basin, bituminous	2.3	25.5	64.4	7.8	1.1	13,780
Michigan						
Saginaw district, bituminous	11.9	31.5	49.8	6.8	1.2	11,780

[a] Analyses made by the Iowa State University.

[b] Analyses made by the Maryland Geological Survey. Each analysis is the average of all analyses of a certain coal bed in that basin or field.

TABLE I.—ANALYSES OF REPRESENTATIVE COALS OF THE UNITED STATES—*Continued*

Location and rank of coal	Moisture	Volatile matter	Fixed carbon	Ash	Sulphur	Heat value (B.t.u.)
Missouri						
Putnam County, bituminous	18.5	32.6	39.0	9.9	4.1	10,040
Harrison County, bituminous	15.3	37.1	40.8	6.8	3.0	10,100
Adair County, bituminous	15.4	34.8	38.8	11.0	3.6	10,460
Grundy County, bituminous	11.7	38.8	38.8	10.7	5.1	11,020
Macon County, bituminous	13.8	34.7	41.8	9.7	3.3	10,960
Randolph County, bituminous	12.1	36.3	42.9	8.7	3.9	11,450
Audrain County, bituminous	10.4	39.3	38.0	12.3	4.9	11,350
Ray County, bituminous	15.8	32.8	41.5	9.9	3.0	10,620
Lafayette County, bituminous	12.3	34.4	42.0	11.3	4.6	11,000
Henry County, bituminous	10.6	37.2	40.7	11.5	3.6	11,250
Bates County, bituminous	7.8	35.5	44.0	12.7	5.2	11,740
Vernon County, bituminous	6.5	32.6	50.8	10.1	5.0	12,460
Barton County, bituminous	5.4	32.1	53.6	8.9	3.6	12,990
Montana						
Culbertson district, lignite	40.8	25.2	27.8	6.2	0.7	6,150
Glendive district, lignite	34.6	35.3	22.9	7.2	1.1	7,090
Miles City district, subbituminous (?)	29.2	26.2	35.4	9.2	0.8	7,670
Havre district, subbituminous	25.6	27.9	39.2	7.3	0.6	8,290
Cutbank district, bituminous	6.6	40.3	39.2	13.9	3.1	10,930
Lewiston district, bituminous	8.0	26.6	56.1	9.3	4.4	11,510
Sand Coulee district, bituminous	6.0	28.4	51.4	14.2	2.4	11,150
Roundup district, subbituminous	13.4	32.4	47.6	6.6	0.4	11,120
Bridger district, bituminous	9.8	27.6	46.2	16.4	0.6	10,240
Bear Creek district, subbituminous	10.7	34.1	46.1	9.1	1.5	10,800
Red Lodge district, subbituminous	11.7	36.1	40.2	12.0	1.1	9,790
Trail Creek field, bituminous	12.4	36.8	42.3	8.5	0.6	10,950
Electric field, bituminous, coking	4.0	22.5	59.3	14.2	0.6	12,760
Missoula field, lignite	24.7	29.3	26.1	19.9	0.9	6,730
Nevada						
Esmeralda County, bituminous	2.1	33.7	33.7	30.5	7.2	9,590
New Mexico						
Raton field, bituminous, coking	2.1	36.1	50.2	11.6	0.6	12,970
Los Cerrillos field, anthracite	5.7	2.2	86.1	6.0	0.7	13,270
Los Cerrillos field, bituminous	3.2	41.4	44.4	11.0	1.6	12.450
Carthage field, bituminous, coking	3.0	38.0	51.6	7.4	0.9	13,260
White Oaks field, bituminous	2.5	37.9	44.9	14.7	0.8	12,260
Monero district, bituminous, coking	3.0	39.0	48.3	9.7	3.5	12,930
Gallup district, subbituminous	12.7	36.5	43.3	7.5	0.7	11,230
North Dakota						
Ward County, lignite[a]	36.5	28.4	28.7	6.4	1.4	6,750
Mountrail County, lignite[a]	37.8	30.1	24.3	7.8	0.6	6,230
Williams County, lignite	41.1	27.2	26.3	5.4	0.7	6,490
Northern McLean County, lignite[a]	40.0	29.7	27.1	3.2	0.3	6,610
Southern McLean County, lignite	40.5	27.1	27.4	5.0	0.8	6,640
Morton County, lignite	38.5	27.6	26.6	7.3	1.3	6,700
Stark County, lignite[a]	40.5	26.3	27.0	6.2	0.8	6,210
Billings County, lignite[a]	37.0	26.3	28.7	8.0	1.8	6,590
Adams County, lignite	32.4	30.9	28.1	8.6	1.5	7,330
Bowman County, lignite	41.4	23.9	28.4	6.3	0.7	6,240
Ohio						
Stark County, bituminous[b]	6.7	36.2	48.9	8.2	2.7	12,560
Tuscarawas County, bituminous[b]	4.7	39.2	49.9	6.2	3.3	12,770

[a] Analyses made by North Dakota Geological Survey.

[b] Analyses made by the Ohio Geological Survey.

TABLE I.—ANALYSES OF REPRESENTATIVE COALS OF THE UNITED STATES—*Continued*

Location and rank of coal	Moisture	Volatile matter	Fixed carbon	Ash	Sulphur	Heat value (B.t.u.)
Ohio—Continued						
Jefferson County, bituminous	4.1	38.5	49.7	7.7	3.7	13,150
Coshocton County, bituminous[a]	4.5	38.7	50.8	6.0	3.6	12,910
Belmont County, bituminous	3.9	43.1	43.9	9.1	4.4	12,840
Guernsey County, bituminous	6.0	34.2	52.0	7.8	2.0	12,720
Noble County, bituminous	3.6	41.5	44.4	10.5	4.9	12,510
Perry County, bituminous[a]	6.7	37.1	49.1	7.1	2.6	12,390
Washington County, bituminous[a]	3.4	37.9	49.1	9.6	5.0	12,750
Hocking County, bituminous[a]	7.5	34.0	52.6	5.9	0.8	12,510
Meigs County, bituminous[a]	7.2	32.8	50.7	9.3	1.3	12,000
Jackson County, bituminous[a]	5.3	41.0	45.3	8.4	3.7	12,210
Lawrence County, bituminous	7.1	33.7	50.3	8.9	1.3	12,090
Oklahoma						
Craig County, bituminous	4.1	37.4	48.3	10.2	6.1	12,920
Rogers County, bituminous	4.2	38.2	47.8	9.8	5.2	13,010
Tulsa County, bituminous	6.3	37.7	47.8	8.2	8.2	12,690
Okmulgee County, bituminous	7.5	32.9	51.0	8.6	1.5	12,410
Haskell County, semibituminous	2.7	21.1	69.9	6.3	0.8	14,100
Le Flore County, semibituminous	3.1	31.7	58.9	6.3	0.9	14,020
Latimer County, bituminous	3.0	36.0	55.9	5.1	1.1	13,710
Pittsburg County, bituminous	3.6	33.4	58.0	5.0	0.5	13,740
Coal County, bituminous	6.5	39.0	45.2	9.3	3.7	11,840
Oregon						
Coos Bay field, subbituminous	18.0	31.8	39.7	10.5	2.2	8,910
Eden Ridge field, bituminous	12.6	35.0	37.7	14.7	1.3	10,350
Pennsylvania						
Anthracite region, anthracite	2.8	1.2	88.2	7.8	0.9	13,300
Do	2.2	5.7	86.2	5.9	0.6	13,830
Sullivan County, semianthracite	3.4	9.3	75.6	11.7	0.8	13,120
Tioga County, semibituminous	2.3	20.9	66.9	9.9	1.3	13,620
Elk County, bituminous	2.7	33.7	54.9	8.7	2.9	13,470
Center County, semibituminous	2.9	19.9	69.7	7.5	1.9	14,080
Center County, bituminous	3.5	23.7	61.6	11.2	2.7	13,060
Clearfield County, semibituminous	3.3	19.9	69.0	7.8	2.0	14,020
Clearfield County, bituminous	2.8	24.3	66.3	6.6	0.9	14,130
Indiana County, bituminous	1.0	26.1	63.8	9.1	2.7	13,950
Butler County, bituminous	4.6	33.0	54.4	8.0	1.3	13,200
Cambria County, semibituminous, high rank	3.3	12.5	77.9	6.3	1.0	14,340
Cambria County, semibituminous, low rank	2.0	21.2	70.9	5.9	1.2	14,510
Cambria County, bituminous	3.1	26.0	64.4	6.5	1.4	14,160
Westmoreland County, bituminous, coking	2.7	30.4	57.8	9.1	1.3	13,610
Allegheny County, bituminous	3.7	34.0	56.8	5.5	1.4	13,870
Broadtop field, semibituminous	2.1	15.5	76.0	6.4	1.1	14,470
Somerset County, semibituminous, high rank	2.5	12.5	78.8	6.2	1.1	14,380
Somerset County, semibituminous, low rank	2.6	21.5	68.0	7.9	1.7	13,900
Fayette County, bituminous, coking	2.8	30.0	59.8	7.4	1.2	13,990
Washington County, bituminous	1.4	34.6	57.8	6.2	0.8	14,240
Rhode Island						
Portsmouth district, anthracite	13.2	2.6	65.3	18.9	0.3	9,310
South Dakota						
Harding County, lignite	41.5	24.0	24.3	10.2	0.6	5,650
Tennessee						
Claiborne and Campbell counties, bituminous	3.6	37.3	55.5	3.6	1.1	13,080
Scott and Fentress counties, bituminous	3.8	38.5	51.2	6.5	1.9	13,400

[a] Analyses made by the Ohio Geological Survey.

Table I.—Analyses of Representative Coals of the United States—*Continued*

Location and rank of coal	Moisture	Volatile matter	Fixed carbon	Ash	Sulphur	Heat value (B.t.u.)
Tennessee—Continued						
Anderson County, bituminous	2.2	37.2	54.5	6.1	1.6	13,960
Morgan County, bituminous	2.0	37.5	52.6	7.9	4.0	13,810
Roane and Rhea counties, bituminous, coking	2.2	29.6	59.4	8.8	0.5	13,620
Cumberland County, bituminous	4.3	25.7	62.5	7.5	0.6	13,630
Overton County, bituminous	3.4	35.6	50.6	10.4	3.1	12,990
White County, bituminous	3.0	39.7	46.9	10.4	4.1	13,950
Hamilton County, bituminous	2.9	29.9	59.2	8.0	1.2	13,760
Bledsoe and Sequatchie counties, bituminous	3.0	29.8	58.9	8.3	1.0	13,560
Grundy County, bituminous	3.6	29.8	57.9	8.7	1.4	13,330
Marion County, bituminous	3.4	28.2	60.1	8.3	0.8	13,430
Texas						
Houston County, lignite	33.5	39.5	16.2	10.8	0.6	7,140
Wood County, lignite	28.9	35.9	27.3	7.9	0.5	8,000
Milam County, lignite	36.0	27.9	28.7	7.4	0.8	7,130
Utah						
Summit County, subbituminous	14.2	36.0	44.8	5.0	1.4	10,630
Uinta County, bituminous	8.6	36.1	47.2	8.1	1.4	11,580
Grand County, bituminous	7.1	37.0	45.4	10.5	0.7	11,720
Carbon County, bituminous	4.4	38.2	50.5	6.9	0.8	12,760
Emery County, bituminous	7.2	42.2	44.8	5.8	0.7	12,540
Iron and Kane counties, anthracite	8.2	4.4	58.0	29.4	2.3	8,910
Iron and Kane counties, semibituminous	9.5	13.2	49.2	28.1	3.6	8,860
Iron and Kane counties, bituminous	10.4	36.3	43.7	9.6	5.8	10,870
Virginia						
Appalachian region:						
Tazewell County, semibituminous	3.8	15.5	77.8	2.9	0.6	14,860
Buchanan County, semibituminous	2.4	19.6	64.6	13.4	0.7	13,100
Buchanan County, bituminous	3.5	31.9	60.9	3.7	1.5	14,390
Dickinson County, bituminous	3.0	32.4	58.4	6.2	1.6	14,030
Russell County, bituminous	2.8	34.9	56.5	5.8	0.6	14,150
Wise County, bituminous, coking	2.5	31.7	60.3	5.5	0.5	14,250
Lee County, bituminous	3.4	34.4	58.8	3.4	0.6	14,130
Montgomery County, semibituminous	1.6	12.3	68.1	18.0	0.5	12,340
Richmond Basin, bituminous	2.8	25.7	62.5	9.0	1.4	13,490
Washington						
Whatcom County, anthracite	4.4	7.4	76.0	12.2	1.0	12,590
King County:						
Newcastle district, subbituminous	12.1	36.8	40.7	10.4	0.3	10,410
Grand Ridge district, subbituminous	15.9	36.0	38.5	9.6	0.5	9,970
Snoqualmie district, bituminous	6.1	22.7	58.8	12.4	0.9	10,710
Renton district, subbituminous	14.4	36.1	42.0	7.5	0.6	10,560
Taylor district, bituminous	5.6	35.9	44.1	14.4	0.9	11,550
Ravensdale district, bituminous	7.4	37.4	43.9	11.3	0.5	11,500
Black Diamond district, bituminous	6.8	40.0	47.9	5.3	1.4	12,330
Bayne district, bituminous	4.1	32.8	52.8	10.3	0.5	12,780
Pierce County:						
Burnett district, bituminous	3.2	35.0	49.3	12.5	0.4	12,720
Gale Creek district, bituminous	2.8	33.8	53.9	9.5	1.0	13,450
Wilkeson district, bituminous, coking	2.5	27.7	61.3	8.5	0.4	13,890
Wilkeson district, semibituminous	3.6	19.1	61.3	16.0	0.5	12,320
Carbon Hill district, bituminous	3.4	32.2	49.5	14.9	0.5	12,250
Fairfax district, bituminous	3.6	23.6	59.3	13.5	0.4	12,750
Fairfax district, semibituminous	4.0	18.1	58.5	19.4	0.5	11,820
Fairfax district, semianthracite	9.2	9.4	63.7	17.7	0.7	11,130

TABLE I.—ANALYSES OF REPRESENTATIVE COALS OF THE UNITED STATES—*Continued*

Location and rank of coal	Moisture	Volatile matter	Fixed carbon	Ash	Sulphur	Heat value (B.t.u.)
Washington—Continued						
Kittitas County:						
Beekman district, bituminous	3.3	34.1	50.5	12.1	0.4	12,910
Roslyn district, bituminous	4.7	36.0	46.8	12.5	0.4	12,240
Cle Elum district, bituminous	5.0	36.1	46.8	12.1	0.4	11,900
Thruston County:						
Centralia district, subbituminous	21.0	33.1	36.7	9.2	0.4	8,910
West Virginia						
Wheeling district, bituminous	4.1	36.6	53.3	6.0	2.1	13,400
Moundsville district, bituminous	3.4	41.6	48.0	7.0	3.3	13,310
Fairmont district, bituminous	2.9	34.5	56.9	5.7	0.7	14,040
Clarksburg district, bituminous	2.8	38.5	53.1	5.6	2.4	14,110
Upper Potomac basin, semibituminous, high rank	1.1	17.2	73.8	7.9	1.1	14,490
Upper Potomac basin, semibituminous, low rank	1.2	20.4	70.8	7.6	1.0	14,520
Preston County, bituminous	3.6	27.4	62.8	6.2	0.9	14,220
Buckhannon district, bituminous	2.5	32.5	56.3	8.7	1.7	13,590
Sutton district, bituminous[a]	2.3	38.3	52.9	6.5	2.1	13,530
Clay district, bituminous	2.8	35.5	54.7	7.0	0.8	13,700
Winfield district, bituminous	5.0	39.6	48.3	7.1	1.8	13,000
New River field:						
New River district, semibituminous, high rank	4.0	14.1	73.7	8.2	0.8	13,850
New River district, semibituminous, low rank	3.5	22.2	71.9	2.4	0.7	14,690
Beckley district, semibituminous, high rank	4.7	13.0	77.9	4.4	0.8	14,340
Beckley district, semibituminous, low rank	3.3	18.0	75.6	3.1	0.8	14,660
Montgomery district, bituminous	2.4	35.5	56.7	5.4	1.0	14,160
Coalburg district, bituminous	3.4	35.2	53.1	8.3	0.7	13,300
Logan district, bituminous	3.3	33.3	58.4	5.0	0.7	14,050
Thacker district, bituminous, high rank	3.1	31.4	59.9	5.6	1.2	14,050
Thacker district, bituminous, low rank	4.5	38.8	50.9	5.8	2.0	13,370
Iaeger district, semibituminous	2.0	19.9	70.4	7.7	0.7	14,110
Pocahontas field, semibituminous, low rank	3.4	22.5	68.8	5.3	0.5	14,370
Widemouth district, semibituminous, medium rank	3.1	18.2	74.8	3.9	0.7	14,690
Welch district, semibituminous, high rank	2.8	12.5	80.4	4.3	0.7	14,660
Wyoming						
Sheridan district, subbituminous	22.6	32.5	40.4	4.5	0.3	9,220
Bighorn Basin field, subbituminous	16.5	32.9	45.8	4.8	0.6	10,750
Black Hills region, bituminous, coking	10.0	39.1	34.3	16.6	4.9	10,250
Glenrock district, subbituminous	21.9	34.0	37.4	6.7	0.9	9,070
Hudson district, subbituminous	21.1	31.4	41.7	5.8	0.5	9,460
Hanna Basin field, subbituminous	11.5	42.6	39.3	6.6	0.4	10,890
Rock Springs field, bituminous	9.8	34.3	52.5	3.4	1.0	12,260
Kemmerer district, bituminous	5.7	37.7	51.3	5.3	1.4	12,580
Kemmerer district, subbituminous	20.6	36.3	40.5	2.6	0.5	10,240
Evanston district, subbituminous	14.4	36.8	41.6	7.2	0.2	10,440

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[a] **Analysis by West Virginia Geological Survey.**

CHAPTER II

THE PRINCIPLES OF COMBUSTION*

By

ARTHUR D. PRATT†

Combustion is the continuous combination of a substance with certain elements, as oxygen, chlorine, etc., accompanied by light and heat. Oxygen is ordinarily referred to as the supporter of combustion, and a "combustible" therefore may be defined as a substance capable of combining with oxygen to produce heat.

Combustion is dependent upon the affinity of the combustible for oxygen, though conditions under which combustion takes place may somewhat affect the speed. While combustion may be rapid or slow, as limited to the production of heat for commercial purposes, it is commonly defined as the rapid combination of the combustible elements of fuel with oxygen; in this particular sense the term combustible implies the capacity of an element for combining with oxygen to produce head.

The elementary substances encountered in combustion work are hydrogen and sulphur. Of these, carbon, hydrogen and sulphur are the combustible elements, the first two being the most important. The elementary substances met with and some of the combustible compounds found in the fuels used for commercial heat generation are given in Table II.

Air.—The necessary supporter of combustion, oxygen, is obtained from the air.

Air is a mechanical mixture of oxygen, nitrogen, and small quantities of carbon dioxide, water vapor, argon and other inert gases. In commercial combustion the carbon dioxide and other inert gases are ordinarily included with the nitrogen; and of the slightly varying proportions of oxygen and nitrogen

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* This Chapter has been prepared primarily to meet the needs of the factory executive and industrial engineer. Therefore, it is purposely demochemical in character. For a technical consideration of combustion, see Bone's "Coal and Its Scientific Uses," 1918, 164 and 184.

† The Babcock and Wilcox Company, New York, N. Y.

TABLE II.—ELEMENTS AND COMPOUNDS OF IMPORTANCE IN COMBUSTION

Substance	Molecular formula	Atomic weight		Molecular weight		Form
		Accurate	Approximate	Accurate	Approximate	
Carbon	C[*]	12.005	12	[†]	..	Solid
Hydrogen	H_2	1.008	1	2.015	2	Gas
Oxygen	O_2	16.00	16	32.00	32	Gas
Sulphur	S_2	32.07	32	64.14	64	Solid
Nitrogen[‡]	N_2	14.01	14	28.02	28	Gas
Carbon monoxide	CO	......	..	28.01	28	Gas
Carbon dioxide	CO_2	......	..	44.01	44	Gas
Methane	CH_4	......	..	16.03	16	Gas
Acetylene	C_2H_2	......	..	26.03	26	Gas
Ethylene	C_2H_4	......	..	28.03	28	Gas
Ethane	C_2H_6	......	..	30.05	30	Gas
Sulphur dioxide	SO_2	......	..	64.07	64	Gas
Hydrogen sulphide	H_2S	......	..	34.08	34	Gas
Water vapor	H_2O	......	..	18.02	18	Vapor
Air	....	......	..	28.94	29	Gas

[*] Atomic symbol.

[†] The molecular weight of C has not been determined definitely. Carbon exists in a number of forms, each of which probably has its own molecular weight. The latest investigations indicate that a molecule of carbon in any form consists of at least 12 atoms.

[‡] Atmospheric nitrogen as distinguished from chemically pure nitrogen which has an atomic weight slightly less than 14.01.

given by different authorities, the generally accepted values are as follows:

	BY VOLUME PER CENT.	BY WEIGHT PER CENT
O_2	20.91	23.15
N_2	79.09	76.85

The oxygen, with its strong affinity for the combustible constituents of the fuel, under proper temperature conditions to be discussed hereafter, enters into chemical combination with the available combustible. The nitrogen serves no direct function in combustion and is the source of a direct loss in that it must be heated to the ultimate temperature of the products of combustion, thereby absorbing heat; but it thus acts as a carrier of heat.

The chemical reactions between elements or compounds—that is, the rearrangement of the atoms of the constituent elements into new combinations of molecules—always occur in accordance with fixed and invariable weight relations which are characteristic of the elements involved, and the combination of oxygen with the combustible elements and compounds of a fuel follows such fixed laws.

The chemical reactions of commercial combustion are simple and may be computed from the molecular weights given in Table II. Assuming complete combustion and that the exact amount of oxygen required is supplied and utilized,* these reactions and the resulting combinations are as given in Table III.

TABLE III.—CHEMICAL REACTIONS OF COMBUSTION

Combustible substance	Reaction
Carbon (to CO)	$2C + O_2 = 2CO$
Carbon (to CO_2)	$2C + 2O_2 = 2CO_2$
Carbon monoxide	$2CO + O_2 = 2CO_2$
Hydrogen	$2H_2 + O_2 = 2H_2O$
Sulphur (to SO_2)	$S + O_2 = SO_2$
Sulphur (to SO_3)	$2S + 3O_2 = 2SO_3$
Methane	$CH_4 + 2O_2 = CO_2 + 2H_2O$
Acetylene	$2C_2H_2 + 5O_2 = 4CO_2 + 2H_2O$
Ethylene	$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O$
Ethane	$2C_2H_6 + 7O_2 = 4CO_2 + 6H_2O$
Hydrogen sulphide	$2H_2S + 3O_2 = 2H_2O + 2SO_2$

It appears from this table that carbon may enter into combination with oxygen to form either carbon monoxide, in which the carbon has not combined with all the oxygen with which it is capable of entering into combination, and carbon dioxide, in which it has combined with all the oxygen possible. Carbon monoxide, however, may combine with additional oxygen, to form carbon dioxide, and in this way all the carbon of the original combination may become oxidized completely. The fact that carbon may enter into these two combinations with oxygen is of the greatest importance in commercial heat generation and will be considered at more length *infra*.

Temperature.—The speed of combustion is, as stated, dependent upon the affinity of the combustible substance for oxygen and the conditions under which combustion takes place. The chief of these conditions is that of temperature, and this factor must be considered before discussing the effects of excess or insufficient oxygen on combustion.

The mere fact that a combustible substance is brought into the presence of oxygen does not of necessity cause combustion to follow. Every combustible substance has a temperature called

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* See complete *vs.* perfect combustion, page 63.

its *ignition temperature,* to which it must be brought before it will unite in chemical combination with oxygen and below which actual combustion will not take place; and this ignition temperature must exist with oxygen present or there will be no combustion.

The ignition temperature of different combustible substances varies greatly. These temperatures for various fuels and for the combustible constituents of commercial fuels are given in Table IV.

TABLE IV.—IGNITION TEMPERATURES

Combustible substance	Molecular formula	Ignition temperature, degrees Fahrenheit
Sulphur	S_2	470
Fixed carbon—bituminous coal	....	766
Fixed carbon—semibituminous coal	....	870
Fixed carbon—anthracite coal	....	925
Acetylene	C_2H_2	900
Ethane	C_2H_6	1,000
Ethylene	C_2H_4	1,022
Hydrogen	H_2	1,130
Methane	CH_4	1,202
Carbon monoxide	CO	1,210

It is of interest to note that the temperatures of ignition of the gases of a coal are considerably higher than the ignition temperature of the fixed carbon constituent. Since the gaseous constituents ordinarily are distilled off, though not ignited, before the ignition temperature of the fixed carbon content is attained, this latter temperature is the ignition temperature of the coal.

If the heat evolved in combustion is sufficient to maintain the temperature of the substance above the ignition point, combustion will continue. If the amount of heat evolved is not sufficient, combustion will cease as soon as the external source of heat which brought the substance to the ignition point is removed.

GASES; DENSITY, WEIGHT AND VOLUME

In the computation of combustion data a knowledge of the density, weight and volume of air and of the gases of commercial combustion is necessary.

The *density* of a gas, ordinarily referred to that of air as standard, is the weight of a unit volume of the gas divided by the weight of an equal volume of pure dry air, the conditions of temperature and pressure being the same.

The *weight per cubic foot* of a gas, under standard conditions called the *specific weight*, may be computed directly from its density and the weight of air at the same temperature and pressure.

The *specific volume* of a gas, or the volume per pound, is the reciprocal of its specific weight.

The standard conditions mentioned are ordinarily accepted as a pressure of 14.6963 lb. per square inch (2116.27 lb. per square foot) and a temperature of 32°F. In practically all combustion work at or near sea level this standard pressure may be assumed, the variation in temperature alone being considered.

The volume and weight of air at atmospheric pressure and varying temperatures are given in Table V.

Table V.—Volume and Weight of Air
At atmospheric pressure

Temperature, degrees Fahrenheit	Volume 1 lb., cubic foot	Weight per cubic foot, pounds	Temperature, degrees Fahrenheit	Volume 1 lb., cubic foot	Weight per cubic foot, pounds	Temperature, degrees Fahrenheit	Volume 1 lb., cubic foot	Weight per cubic foot, pounds
32	12.390	0.080710	160	15.615	0.064041	340	20.151	0.049625
50	12.843	0.077863	170	15.867	0.063024	360	20.655	0.048414
55	12.969	0.077107	180	16.119	0.062039	380	21.159	0.047261
60	13.095	0.076365	190	16.371	0.061084	400	21.663	0.046162
65	13.221	0.075637	200	16.623	0.060158	425	22.293	0.044857
70	13.347	0.074923	210	16.875	0.059259	450	22.923	0.043624
75	13.473	0.074223	212	16.925	0.059084	475	23.554	0.042456
80	13.599	0.073535	220	17.127	0.058388	500	24.184	0.041350
85	13.725	0.072860	230	17.379	0.057541	525	24.814	0.040300
90	13.851	0.072197	240	17.631	0.056718	550	25.444	0.039302
95	13.977	0.071546	250	17.883	0.055919	575	26.074	0.038352
100	14.103	0.070907	260	18.135	0.055142	600	26.704	0.037448
110	14.355	0.069662	270	18.387	0.054386	650	27.964	0.035760
120	14.607	0.068460	280	18.639	0.053651	700	29.224	0.034219
130	14.859	0.067299	290	18.891	0.052935	750	30.484	0.032804
140	15.111	0.066177	300	19.143	0.052238	800	31.744	0.031502
150	15.363	0.065092	320	19.647	0.050898	850	33.004	0.030299

The density, weight and volume of the commercial gases of combustion under standard conditions are given in Table VI.

TABLE VI.—DENSITY, WEIGHT AND VOLUME OF GASES
At atmospheric pressure and 32°F.

Substance	Molecular formula	Relative density		Weight per cubic foot, pounds	Cubic feet per pound, cubic foot	Value of constant R in $PV = RT$
		Air = 1	Hydrogen = 1*			
Air	......	1.0000	..	0.08071	12.390	53.33
Oxygen	O_2	1.1053	16	0.08921	11.209	48.24
Hydrogen	H_2	0.0696	1	0.00562	177.936	765.8
Nitrogen	N_2	0.9673	14	0.07807	12.809	55.13
Carbon monoxide	CO	0.9672	14	0.07806	12.811	55.15
Carbon dioxide	CO_2	1.5291	22	0.12341	8.103	34.88
Methane	CH_4	0.5576	8	0.04500	22.222	95.64
Acetylene	C_2H_2	0.9200	13	0.07425	13.468	57.97
Ethylene	C_2H_4	0.9674	14	0.07808	12.807	55.12
Ethane	C_2H_6	1.0494	15	0.08470	11.806	50.81
Sulphur dioxide	SO_2	2.2639	32	0.18272	5.473	23.56
Carbon†‡	......	......	..	145	0.0069	
Sulphur	S_2	......	..	125	0.0080	

* Based on approximate molecular weights.

† Solid.

‡ If carbon could be conceived to exist as a gas under standard conditions, its relative density would be 0.820, its weight per cubic foot 0.0668 pounds, and its volume 14.97 cu. ft. per pound.

The weight of these gases under standard pressure and other than standard temperature, may, as stated, be computed from Table V, and the relative densities, the volumes at other pressures being the reciprocals of such weights. Or the volume may be computed for any other than standard conditions from the characteristic equation of a perfect gas:

$$PV = RT,$$

where

P = Absolute pressure, pounds per square foot.

V = Volume per pound, in cubic feet.

T = Absolute temperature.

R = A constant varying with the gas and derived from the relations existing between the pressure, volume and temperature of the gas in question. The relation is represented by the expression, $T = P_O V_O / T_O$, the pressure and temperature being the standard and the volume that under such standard.

Conversion of Analyses.—In combustion work, gas analyses* are frequently given in terms of volume when analyses in terms of weight are required. To convert a volumetric analysis to one by weight, the percentage by volume of each constituent gas should be multiplied by its relative density, each product being divided by the sum of the products. To convert an analysis by weight to one in terms of volume, the percentage by weight of each constituent should be divided by the sum of the quotients. Since the molecular weights of the various gases bear the same relations to each other as the relative densities, these molecular weights may be used in transforming analyses instead of the relative densities.

Another method of converting volumetric analyses to analyses in terms of percentage by weight is through the use of the weights per cubic foot of the various constituent gases. The percentages by volume are multiplied by the weights per cubic foot, and each product is divided by the sum of the products. This method has an advantage in that it gives directly, in the sum of the products, the weight of the gas as a whole per cubic foot.

HEAT OF COMBUSTION

When elements enter into combination to form a compound, a definite amount of heat, called the *heat of combination,* is either evolved or absorbed. When a compound is decomposed into its constituent elements, the amount of heat absorbed or evolved is exactly the same as that which was evolved or absorbed in the original formation of the compound. In complex chemical changes involving both combination and decomposition, the heat produced or absorbed is the net result of the two reactions.

Heat of Combustion.—Commercial combustion has been defined as the rapid chemical combination of the combustible constituents of a fuel and oxygen, with a resulting production of heat. The heat of combustion of a fuel is obviously, then, the heat evolved in the complete oxidation of its combustible constituents, and is thus the heat of combination of a specific set of elements and compounds, the combination of which with oxygen results in the production of heat.

The heat energy evolved through the union of the combustible constituents of a fuel with oxygen is dependent upon the final products of combustion and in no way upon any intermediate

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* See A. H. White's "Technical Gas and Fuel Analysis," 2d ed.

combination that may have occurred in reaching the final result. This may be most readily shown by the following example:

A coal fire, from which all the volatile constituents have been driven and which consists of incandescent coke, may for the present purpose be considered as consisting entirely of carbon. If air is introduced under the fire, the oxygen immediately enters into chemical combination with carbon to form carbon dioxide ($C + 2O = CO_2$). Each unit of carbon has combined with the maximum amount of oxygen with which it can exist as a compound. The oxygen, on the other hand, is capable of uniting with additional carbon, and, as the unit of carbon dioxide passes upward through the fuel bed under the influence of draft, it encounters other free carbon, with which it unites to form carbon monoxide ($CO_2 + C = 2CO$). If no additional oxygen is encountered in the further passage through the fuel bed, the gas, as representative of the products of combustion, will issue from the fuel bed as carbon monoxide. If no additional oxygen is encountered in the furnace, the total heat available for later absorption by the boiler is that due to the combustion of carbon to carbon monoxide, regardless of the fact that at one stage of the process the carbon had been oxidized completely and carbon dioxide had been produced. If, on the other hand, additional oxygen is encountered in the furnace, the temperature is above the ignition point of carbon monoxide, and this temperature is maintained a sufficient length of time for further combustion; *i.e.*, if the gases are not cooled below the ignition temperature by the boiler heating surface before further conbustion can be completed, the carbon of the carbon monoxide will unite with additional oxygen to form carbon dioxide ($2CO + 2O = 2CO_2$). The total heat evolved and available for absorption in such cases will be that due to the burning of carbon to carbon dioxide regardless of the two intermediate steps.

The heat of combustion of a fuel is the amount of heat, expressed in British thermal units, generated by the complete combustion or oxidation of 1 lb. of the fuel in question. The amount of heat so generated is a constant for any given combination of combustible elements and compounds, and is irrespective of the manner in which combustion takes place so long as such combustion is complete.

The unit of measure of quantity of heat is, as stated, the *British thermal unit* (B.t.u.). This is 1/180 of the amount of heat necessary to raise the temperature of 1 lb. of water from 32° to 212°F.

The heats of combustion of what may be termed the "pure fuels" of commercial combustion, whether elements or compounds, are given in Table VII.

TABLE VII.—HEATS OF COMBUSTION
By calorimetric determination

Combustible	Molecular formula	Heat value—B.t.u. per pound		Per cubic foot‡
		Higher	Lower or net†	Higher
Hydrogen	H_2	62,000	52,920	348
Carbon (to CO)	C	4,380	......	
Carbon (to CO_2)	C	14,540		
Carbon monoxide	CO	4,380	......	342
Carbon in CO§	C	10,160		
Methane	CH_4	23,850	21,670	1,073
Acetylene	C_2H_2	21,460	21,020	1,590
Ethylene	C_2H_4	21,450	20,420	1,675
Ethane	C_2H_6	22,230	20,500	1,883
Sulphur (to SO_2)	S_2	4,050		
Sulphur (to SO_3)	S_2	5,940		

† There is a considerable discrepancy between lower heat values as given by different authorities, the variation being due to methods of computation and assumptions. The values given are those of G. A. Goodenough.

‡ At 32°F. and atmospheric pressure.

§ Per pound of carbon in carbon monoxide, *i.e.*, 2.33 lb. of CO.

It appears from this table that, in burning to carbon monoxide and to carbon dioxide, carbon has a widely different heat of combustion. That carbon, the chief combustible element of all fuels, may be burned to evolve such different amounts of heat, offers the possible source of one of the greatest combustion losses.

The only accurate and reliable heat value of a fuel is that determined experimentally with a calorimeter. For solid and liquid fuels separate determinations are necessary for each specific fuel. For elements and combustible compounds entering into gaseous fuels the heats of combustion have been determined by so many authorities that definite values may be accepted as correct without determination.

Numerous formulas have been offered by different authorities for the computation of the heat of combustion of various fuels. Such formulas are ordinarily based on the ultimate analysis of the fuel; and while in certain cases they will give results checking closely with calorimetric determinations, they are not applicable to all fuels. Because of the sources of possible error in the assumptions of formulas of this character, their use, particularly for solid and liquid fuels, should be confined to cases where only the most approximate results are desired. In the case of gaseous fuels, as stated, provided the analysis is known to be accurate, the heat value may be computed readily from the values of Table VII.

The heat value of a fuel, as defined, is known as the "higher" heat value and is ordinarily accepted as the standard. From time to time efforts have been made to introduce another value, known as the "lower," "net" or "available" heat value, in the determination of which an attempt is made to allow for the latent heat recovered in the condensation of the water vapor formed in the burning of the hydrogen which is present in practically all fuels. While the net value is in common use in Great Britain and in most foreign countries, because of the sources of error in the correction computations it has never been accepted in this country. The higher value is the standard of the American Society of Mechanical Engineers.

SPECIFIC HEAT

The heat of combustion of any substance must from its nature have an important bearing on the temperature which will result from the burning of such substance. Before such temperatures can be discussed, it is necessary to consider specific heat, a subject of importance in the computation of all combustion data.

The *specific heat* of a substance is the amount of heat expressed in thermal units required to raise a unit weight of the substance through 1° of temperature, the units in this country being one pound and 1°F. The specific heats of all substances vary with the temperature; and since all substances vary in volume or in pressure with changes in temperature, it is necessary to distinguish between specific heat at constant volume and at constant pressure. expressed ordinarily as C_v and C_p, respectively.

Liquids and solids, because of their low coefficients of expansion, vary but little in volume under a temperature change of one degree; and for such substances there is but little difference between the specific heat at constant volume and at constant pressure. With gases, however, because of their high coefficients of expansion, there is a decided difference. The specific heat at constant volume will always be less than the specific heat at constant pressure by the amount of heat required to do the work of expansion against external pressure.

Under both specific heat at constant pressure and that at constant volume, it is necessary to distinguish between *instantaneous* and *mean* specific heat. The instantaneous specific heat of a substance is the amount of heat that must be added to a unit weight at some definite temperature to increase such temperature 1°, under given conditions of pressure or volume. The mean specific heat of a substance, over a given temperature range, is the value by which such range must be multiplied to determine the amount of heat necessary to raise a unit weight of the substance through the range under the conditions of pressure or volume which exist.

It is the mean specific heat of a substance that is used in the computation of combustion data.

From the definition of a B.t.u. as now accepted, namely, $\frac{1}{180}$ of the heat required to raise 1 lb. of water from 32° to 212°F., when the specific heat of water is given as unity, such value is the mean specific heat over the temperature range 32 to 212°.

Except in the case of water vapor, the variation with pressure in the specific heats of the gases encountered in commercial combustion work is negligible. With water vapor, were it necessary to deal with any considerable range of pressures, such variation would be appreciable; but the partial pressure exerted by water vapor in any of the commercial gases, either before or after combustion, is rarely over one pound absolute. With such a limited pressure range, and in view of the ordinarily small water vapor content of gases, the effect of the variation in pressure upon the specific heat of the gas as a whole may be neglected.

The range of pressures in the gases encountered in commercial combustion is so limited that, in the computation of practically all combustion data, the gases may be assumed to be at constant pressure. The specific heat at constant pressure, then, is the specific heat which should be used, and any results based on the assumption of a constant pressure of the gas as a whole, and in which the variation of the specific heat of the water vapor content with a change of pressure is neglected, will be well within the limits of accuracy of the usual combustion data computations.

While the variation in specific heat with pressure can thus be neglected, the variation with temperature is a very appreciable factor and should be given proper consideration where accurate results are desired.

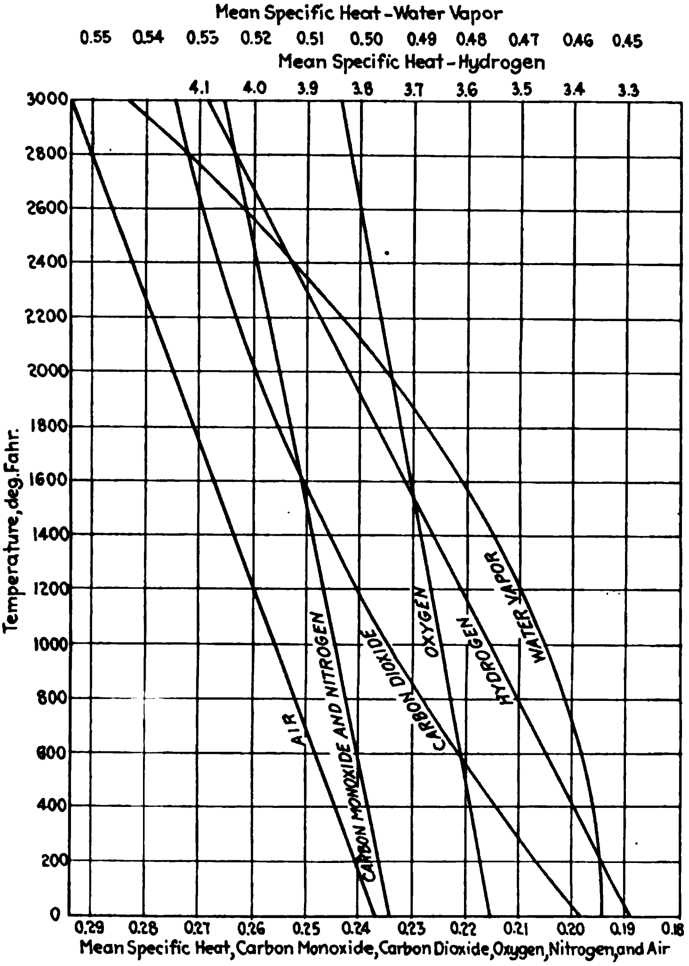

FIG. 2.—Mean specific heats of ordinary gases of combustion.

The general formula for the specific heat of a gas at constant pressure may be expressed by the function—

$$Cp = a + bt + ct^2 + dt^3. \qquad (1)$$

The mean specific heat of a gas over a temperature range $t_1 - t_2$ will be then—

$$Cp\ t_1 - t_2 = a + \frac{b}{2}(t_2 + t_1) + \frac{c}{3}[(t_2 + t_1)^2 - t_2 t_1] + {}^{d}[(t_2 + t_1)(t_2 + t_1)^2 - 2\,t_2 t_1]. \quad (2)$$

Where the lower limit, t_1, of the temperature range is 0°, the mean specific heat over the range $0° - t$ from (2) will be—

$$Cp\ 0 - t = a + \frac{b}{2}t + \frac{C}{3}t^{-2} + \frac{d}{4}t^3. \quad (3)$$

The values of the constants for the gases of commercial combustion in these formulas are given in Fig. 2.

The mean specific heats of these gases at ordinary temperatures are given in Table VIII.

TABLE VIII.—MEAN SPECIFIC HEATS AT CONSTANT PRESSURE AND ORDINARY TEMPERATURES

	Molecular symbol	Mean specific heat	
		0 - 60°F.	0 - 600°F.
Air	......	0.2381	0.2484
Oxygen	O_2	0.2160	0.2211
Hydrogen	H_2	3.3850	3.4750
Nitrogen	N_2	0.2349	0.2406
Carbon monoxide	CO	0.2349	0.2406
Carbon dioxide	CO_2	0.2008	0.2214
Water vapor	H_2O	0.4542	0.4586
Methane*	CH_4	0.498	0.649
Ethylene†	C_2H_4	0.348	0.461
Sulphur dioxide	SO_2	0.1544	

* Methane—$Cp_{o-t} = 0.481 + 0.00028t$

† Ethylene—$Cp_{o-t} = 0.335 + 0.00021t$

TEMPERATURES DEVELOPED IN COMBUSTION

If, in the burning of any fuel, it is assumed—

First, that combustion is complete;

Second, that there is no radiation loss;

Third, that there is no dissociation; and

Fourth, that the inert gases play no part in the reaction, and the total heat generated must be transferred to the products of combustion, and raise their temperature above that of the fuel and the air supplied for combustion a definite amount, depending upon the constituents of the fuel.

Under such assumptions, the theoretical elevation in temperature, from which the temperature developed by the combustion of any fuel can be determined, may be expressed as follows:

$$T = \frac{\text{B.t.u. produced}}{W \times c}, \tag{4}$$

where T = elevation in temperature,
W = weight of products of combustion, and
c = mean specific heat of the products between the temperature of the fuel and air and that of the products.

Since, as has been shown, the value of c in (4) will vary over a considerable range with temperature, this expression cannot be used for a direct temperature computation. It is possible, however, to compute the theoretical temperature resulting from the combustion of a given fuel under given conditions by the use of a method involving trial and error as follows:

Assuming the conditions as given above, the heat energy of a fuel mixture above 0°F., plus the amount of heat generated, must equal the heat energy of the products of combustion above 0°F. If M equals the sum of the fuel constituents $(m^1 + m^2 + m^3 +)$ and M^1 the sum of the constituents of the products of combustion $(m_1 + m_2 + m_3 +)$, the formula for the determination of the theoretical temperature developed may be expressed thus:

$$Mc_pt_1 + \text{Heat Generated}^* = M^1c^1{}_pt_2, \tag{5}$$

where

t_1 = temperature of fuel mixture,
t_2 = temperature evolved in combustion, and
c_p and $c^1{}_p$ = mean specific heats of fuel mixture and products of combustion, respectively.

Since t_2 is unknown, $c^1{}_p$ is also unknown, and, as stated, the method of trial and error must be used.

In the consideration of the theoretical temperature, it is evident that the time element, *i.e.*, the length of time necessary

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[*] It is to be noted, in the case of fuels containing hydrogenous constituents, since no condensation of water vapor occurs, the lower or available heat value of such constituents is the proper value for use in the computations. These values may be taken from Table VIII.

to complete combustion, does not enter, though in actual practice this is an appreciable factor.

In practice, the temperature which, for a given fuel, is theoretically possible, is never obtained. The main factor in the burning of ordinary fuels, which results in a temperature below that theoretically possible, is the dilution of the products of combustion through the introduction of a greater amount of air than is required for complete oxidation, *i. e.*, the presence of excess air. Under such conditions, there are present in the products of combustion amounts of oxygen and nitrogen in excess of the amounts required for combustion, which excess weights must be heated from the temperature at which they are introduced to the ultimate temperature of the gases. In using a portion of the definite amount of heat that a given fuel will generate for so increasing the temperature of these excess weights of oxygen and nitrogen, the temperature of the ultimate mixture will be reduced to below that which would exist were there no excess gases to be heated.

Temperatures below the theoretical will also result from an insufficient air supply. Under such conditions, there is a loss in the heat generated, due to incomplete combustion of carbon (burning to CO instead of CO_2).

A further reduction below the theoretical temperature occurs through loss in radiation. While the time element does not enter into any computation involving formula (5), in practice, since the quantity of heat radiated from a given mass of fuel is a function of the time during which combustion takes place, it is obvious that a portion of the heat generated will be lost through radiation, such loss increasing as combustion is slower.

The two important reactions of combustion,

$$2H_2 + O_2 = 2H_2O \text{ and } 2CO + O_2 = CO_2,$$

are reversible and, if such dissociation occurs, it would have a decided effect on the temperature developed in combustion. The amount of dissociation which takes place under the temperatures developed in boiler furnace practice is not known definitely, but it is probably inappreciable. For commerical combustion this factor may be considered as negligible.

From the factors involved, it is evident that the better the combustion, *i.e.*, the more complete, with the minimum of excess air, the higher the temperature developed. Temperature, therefore, is a measure of the efficiency of combustion, but unfortunately it is difficult with the means available at the present time to determine accurately the actual temperature developed in commercial combustion.

Flame.—The appearance of combustion, *i.e.*, the "look" in the mass of fuel of the products of combustion, offers to the experienced eye a measure of the temperatures developed. While the use of such a method can lead only to the most approximate results, and at best serve simply as a check of more accurate determinations, it is perhaps worth while to consider it briefly.

The physical evidence by which the temperature and the degree and the extent of combustion in a boiler furnace may be judged, is the appearance of the flame, the fuel itself being visible but rarely. *Flame* may be defined as a mass of intensely heated gas in a state of combustion. When solid or liquid fuels appear to burn with a flame, it is because they or certain of their constituents are converted into a gas, either before or during combustion.

Flames are ordinarily classified as oxidizing, neutral, or reducing. An oxidizing flame is the result of combustion in which a greater amount of oxygen (air) has been supplied than that theoretically required for complete combustion, there being left in the products of combustion a supply of oxygen which is available for combination with the combustible constituents of any material being treated. A flame of this character is readily obtainable.

A neutral flame, which has in commercial combustion only a theoretical existence, would be the result of the perfect and complete combustion of any fuel.

A reducing flame is the result of combustion in which less than the amount of oxygen (air) theoretically required for the complete combustion of a fuel has been supplied. With such a flame certain constituents of the products of combustionhave not had their affinity for oxygen "satisfied" and may combine with a portion of the oxygen present in the material being treated. A reducing atmosphere may be readily maintained in an electric furnace, but in other large scale work it is approximated only in the carbon-heated furnace.

The *luminosity* of flame, or the characteristic which gives its visibility, is due to the heating to incandescence of the unconsumed particles of combustible matter present in the gases; and the variation in the colors of flames is due to the difference in the degree of heat communicated to these particles. The higher the temperature of these particles, the whiter the flame. The length and volume of the flame will vary with the combustible elements present, and the thoroughness with which the air and combustible elements are mingled; and, since such number will decrease with an increase in the completeness of combustion, the shorter the flame, in the absence of any outside cooling medium, the more rapid and complete the combustion.

If it were possible for the combustion of any fuel to be complete and instantaneous, there would be no visible luminous flame, since both carbon dioxide and water vapor are invisible. Visible flame, then, is evidence of incomplete or non-combustion, but such evidence in the commercial furnace means simply that the combustion has not taken place with sufficient rapidity to evolve heat instantaneously.

It follows from the above that, for a given amount of fuel burned, a short flame will ordinarily mean rapid and complete combustion, a longer flame delayed combustion, and a very long flame imperfect or non-combustion.

TABLE IX.—TEMPERATURE AND APPEARANCE OF FLAME*

Appearance of flame	Temperature, degrees Fahrenheit
Dark red	975
Dull red	1,290
Dull cherry-red	1,470
Full cherry-red	1,650
Clear cherry-red	1,830
Deep orange	2,010
White	2,370
Bright white	2,550
Dazzling white	2,730

* Jos. W. Hays.

The temperature evolved in combustion may be approximated from the appearance of the fuel mass or the flame in accordance with the preceding table. Such figures are of necessity but the roughest approximations, but, in connection with the flame length, are of some value where apparatus for more accurate determinations of the extent and degree of combustion is not available.

AIR AND COMBUSTION

Thus far, in the abstract consideration of combustion, the presence of sufficient oxygen for combination with oxidizable substances, and a temperature sufficient to bring about the chemical combinations of combustion, have been assumed. Given proper temperature conditions, it is, however, the physical difficulty encountered in the introduction of just the proper amount of oxygen for the best commercial combustion that is the main source of the losses occurring in the burning of any fuel.

The source of supply of oxygen necessary for combustion is, as stated, the air. From the composition of air as given—23.15 per cent of O_2 and 76.85 per cent of N_2, by weight—it is obvious that, to supply 1 lb. of oxygen, it is necessary to supply $1 \div 23.15 = 4.320$ lb. of air, and that for each pound of oxygen so supplied there will be present, and, since it serves no function in combustion, will appear as well in the products of combustion, 3.320 lb. of nitrogen.

From the manner of combinations and dissociations of the chemical reactions of industrial combustion, as given in Table III, and the atomic weights of the elements involved from Table II, the proportionate parts by weight of the elements entering into the compounds may be computed. To illustrate, consider ethylene (C_2H_4):—

The molecular weight of ethylene is 28, or $C_2H_4 = 2C + 4H = 2 \times 12 + 4 \times 1 = 28$. One pound of ethylene, therefore, is composed of 0.857 lb. of carbon and 0.143 lb. of hydrogen.

The carbon content will combine with oxygen to form carbon dioxide, in accordance with the expression $C + 2O = CO_2$, or, expressed in terms of atomic weight, $12 + (2 \times 16) = 44$. Hence carbon dioxide will contain 27.27 per cent of carbon and 72.73 per cent of oxygen by weight, and the ratio of carbon to oxygen in carbon dioxide is thus 1 to 2.667. It follows that, in the burning of 1 lb. of carbon to carbon dioxide, it will be necessary to supply 2.667 lb. of oxygen; and to burn the 0.857 lb. of carbon contained in 1 lb. of ethylene, it is necessary to supply $0.857 \times 2.667 = 2.2856$ lb. of oxygen.

The hydrogen content will combine with oxygen in the relation $2H + O = H_2O$, or $(2 \times 1) + 16 = 18$. Water vapor thus is composed of 11.11 per cent of hydrogen and 88.89 per cent of oxygen by weight, and the ratio of hydrogen to oxygen in water vapor is 1 to 8. Hence, in the burning of 1 lb. of hydrogen, it will be necessary to supply 8 lb. of oxygen; and to burn the 0.143 lb. of hydrogen contained in 1 lb. of ethylene, it is necessary to supply 0.143 × 8 = 1.144 lb. of oxygen.

The weight of air necessary for the combustion of 1 lb. of any substance is directly obtainable from the ratio of oxygen to air, or 1 to 4.32. Considering again ethylene, there will be required to burn 1 lb.—

2[illegible]6 + 1.144 = 3.430 lb. O_2, or 3.430 × 4.32 = 14.82 lb. of air.

The products of combustion of any substance are computed after the manner given above, together with the oxygen-nitrogen ratio of air. The products resulting from the combustion of 1 lb. of ethylene will thus be—

	CO_2	H_2O	N_2
0.857 lb. C + 2.286 lb. O_2 =	3.143	....	....
0.143 lb. H_2 + 1.144 lb. O_2 =	....	1.287	....
(2.286 + 1.144) × 3.32 =	....	....	11.39

The weights of oxygen and air required for the combustion of the constituents of commercial fuels, and the products resulting from such combustion, are given in terms of weight in Table X and in terms of volume in Table XI.

TABLE X.—COMBUSTION DATA

In terms of pounds per pound of fuel

	Molecular formula	Theoretically required, pounds		Products of combustion, pounds				
		O_2	Air	CO_2	H_2O	N_2	CO	SO_2
Carbon (to CO_2)	C	2.667	11.52	3.667	....	8.85	....	....
Carbon (to CO)	C	1.333	5.76	....	....	4.43	2.333	....
Carbon monoxide	CO	0.572	2.46	1.57	....	1.89	....	....
Sulphur	S	1.000	4.32	....	....	3.32	....	2.00
Hydrogen	H_2	8.000	34.56	....	9.00	26.56	....	
Methane	CH_4	4.000	17.28	2.75	2.25	13.28	....	
Acetylene	C_2H_2	3.077	13.29	3.39	0.69	10.21	...	
Ethylene	C_2H_4	3.429	14.81	3.14	1.29	11.38	....	
Ethane	C_2H_6	3.733	16.13	2.93	1.80	12.40	....	
Hydrogen sulphide	H_2S	1.412	6.10	....	0.53	4.69	....	1.88

TABLE XI.—COMBUSTION DATA
In terms of cubic feet per cubic foot of fuel

	Molecular formula	Theoretically required, cubic feet		Products of combustion, cubic feet				
		O_2	Air	CO_2	H_2O	N_2	CO	SO_2
Carbon monoxide....	CO	0.5	2.391	1	..	1.891		
Hydrogen...........	H_2	0.5	2.391	..	1	1.891		
Methane............	CH_4	2.0	9.564	1	2	7.564		
Acetylene..........	C_2H_2	2.5	11.955	2	1	9.455		
Ethylene...........	C_2H_4	3.0	14.346	2	2	11.346		
Ethane.............	C_2H_6	3.5	16.737	2	3	13.237		
Hydrogen sulphide...	H_2S	1.5	7.173	..	1	5.673	....	1

It is well to distinguish here between perfect combustion and complete combustion. *Perfect combustion* is the result of supplying the requisite amount of oxygen for combination with all the oxidizable constituents of the fuel, and utilizing in combustion all the oxygen so supplied. The products of combustion as given in Table III are the products of perfect combustion. *Complete combustion,* on the other hand, results from the oxidation of all the combustible constituents of a fuel, but does not necessarily imply the utilization of all the oxygen supplied. Where combustion is complete but not perfect, therefore, there will be combustion losses resulting from the necessity of heating the excess amount of oxygen and the nitrogen accompanying such excess to the ultimate temperature of the products of combustion.

While in certain commercial processes neither perfect nor complete combustion of a fuel is desired, ordinarily the problem of efficient combustion is that of making complete approach to perfect combustion. Theoretically, preventable losses result from both incomplete combustion and from combustion which is complete but not perfect. It is obvious, therefore, that the real measure of the efficiency of combustion lies in the relations existing between the amount of air theoretically required for perfect combustion and the amount of air actually supplied for such combustion.

The amount of air required for the combustion of the elements and compounds of commercial fuels is given in Table X. For the determination of such weight for a specific fuel, an analysis of that fuel is necessary, and it is perhaps more convenient to express such an analysis in terms of weight even for a gaseous fuel. There are, however, no reliable means of weighing or measuring the amount of air actually supplied for combustion, and such an amount must be computed from an analysis of the products of combustion.

In the ordinary commercial analysis of the products of combustion, the proportionate parts by volume of carbon dioxide, carbon monoxide, and oxygen are determined, the difference between the sum of these constituents and 100 per cent being assumed as nitrogen. In special cases, the products of combustion are examined for hydrocarbons, though this is not usual. In making use of the ordinary commercial analyses, certain assumptions are necessary, but these are such that, provided the analyses are accurate, they will not give results that are in appreciable error.

Where combustion is perfect, the only products of combustion that can result from the burning of any fuel are CO_2, SO_2 (or SO_3), H_2O and N_2. Where combustion is complete but not perfect, there will also appear O_2; while if combustion is neither complete nor perfect, O_2 and CO may appear. The ordinary commercial analysis then is in reality simply a measure of the completeness of combustion of the carbon content of a fuel, though, since SO_2 is absorbed in such an analysis along with the CO_2, it is possible, by making a sulphur correction to the carbon content, to take into consideration the completeness of combustion of the sulphur constituent.

Properly used chemical analyses will, as stated, give combustion data within the required limits of accuracy, but such analyses should be used *only* in conjunction with an analysis of the specific fuel burned. For every fuel there is a definite percentage of carbon monoxide that must correspond to perfect combustion, and hence to zero preventable combustion loss; but such a percentage will vary not only for different classes of fuel, but even widely with different fuels of the same class. No table of CO_2 corresponding to different percentages of preventable loss can be computed that will be applicable to all fuels.

COMBUSTION FORMULAS

Air Required for Combustion.—With carbon, hydrogen and sulphur, the only combustible elements found in commercial fuels, it is a simple matter to construct a formula for the amount of air theoretically required for combustion from the data of Table X. This may be expressed as follows:

Pounds air required per pound of fuel =

$$11.52C + 34.56\left(H_2 - \frac{O_2}{8}\right) + 4.32\ S, \qquad (6)$$

or, more simply,

$$34.56\left(\frac{C}{3} + \left[H_2 - \frac{O_2}{8}\right] + \frac{S}{8}\right), \qquad (6\text{–}a)$$

where C, H_2, O_2 and S are the percentages by weight of carbon hydrogen, oxygen and sulphur, while the constants of the first expression are those of Table X. The term $\left(H_2 - \frac{O_2}{8}\right)$ assumes that all the oxygen constituent is free to unite with the hydrogen to form water vapor. While such an assumption is not correct, strictly speaking, it leads to a negligible error.

In the case of gaseous fuels, in order to make use of the above formula, one assumes that the hydrocarbons are broken into their constituent elements, and it is simpler to construct a formula for such fuels directly from the data of Table X. This formula may be expressed as follows:

Pounds air required per pound fuel =

$$2.46CO + 34.56H_2 + 17.28CH_4 + 13.29C_2H_2 + 14.81C_2H_4 + 16.13C_2H_6 + 6.10H_2S - 4.32O_2. \qquad (7)$$

A similar formula for gaseous fuels, expressed in terms of volume, may be constructed from the data of Table XI.

Products of Combustion.—The data of Table III also make it possible to determine directly what the products of theoretically perfect combustion will be.

Products of combustion per pound of fuel:

$$CO_2 = 3.667C.$$

$$H_2O = 9\left(H - \frac{O}{8}\right) + H_2O.$$

$$SO_2 = 2S.$$

$$N_2 = 8.85C + 26.56H_2 + 3.32S + N_2.$$

With the actual weights of the products of combustion thus known, they may be expressed in terms of percentage by weight, and, if desired, these latter values may be transformed into values giving percentages by volume.

As in the case of air required for combustion, it is perhaps simpler to express the products of combustion of a gaseous fuel directly in terms of the data of Table X.

Products of combustion, 1 lb. of fuel =

$$CO_2 = 1.57CO + 2.75CH_4 + 3.39C_2H_2 + 3.14C_2H_4 + 2.93C_2H_6 + CO_2;$$

$$H_2O = 9\left(H - \frac{O}{8}\right) + 2.25CH_4 + 0.69C_2H_2 + 1.29C_2H_4 + 1.80C_2H_6 + 0.53H_2S + H_2O;$$

$$SO_2 = 1.88H_2S; \text{ and}$$

$$N_2 = 1.89CO + 26.56H_2 + 13.28CH_4 + 10.21C_2H_2 + 12.38C_2H_4 + 12.40C_2H_6 + 4.69H_2S + N_2.$$

As in the case of air required for combustion, it is a simple matter to construct a formula in terms of volume for the theoretical products of perfect combustion from the data of Table XI.

COMBUSTION DATA FROM GAS ANALYSIS

The generally accepted use of a commercial analysis of the products of combustion is its application in a formula which is assumed to give directly the weight of the products of combustion per pound of carbon, which weight, in conjunction with an analysis of the fuel, offers a means, provided a sulphur correction is made to the carbon content, of computing the weight of the products of combustion per pound of fuel burned. This formula is as follows:

$$\text{Pounds of dry gas per pound of carbon} = \frac{11\,CO_2 + 8\,O_2 + 7\,(CO + N_2)}{3\,(CO_2 + CO)}. \qquad (8)$$

Properly used, it will give results well within the limits of accuracy of combustion data computation as a whole. The symbols represent the proportionate parts by volume of the constituents of the gases analyzed. The principal assumption of formula (8) is that the analysis as used is of dry gas.

All fuels in common use contain a greater or less amount of moisture. The loss due to such moisture is computed where a heat balance is given, but the weight of this moisture is sometimes overlooked in computing total gas weight. All air supplied for combustion also contains a certain amount of moisture; and though this weight may be computed and the loss resulting therefrom determined, the weight is ordinarily inappreciable and the loss is commonly included with the unaccounted losses.

Aside from the moisture in the fuel and the air supplied for combustion, which moisture will appear as water vapor in the flue gases, there will also be an appreciable weight of water vapor, due to the burning of the hydrogen content of the fuel. This weight, with perfect combustion, may be as high as 15 per cent of the total for certain gaseous fuels.

We then have present in the flue gases, but not measured in the ordinary analysis, a considerable amount of moisture in the form of water vapor. Water is commonly used as the displacement medium in the collection of the sample of gas for analysis, and further, during the analysis itself, the gas sample comes into contact with water. The effect of these various factors tends toward a saturation of the gas being analyzed and from the results obtained with all classes of fuel the assumption seems warranted that such gases are actually saturated. Under these conditions, proportionate parts of the water vapor content of the gas will be absorbed with the different constituents of such gas and the resulting analysis may be safely assumed to be that of a dry gas.

A further source of error in formula (8) is one resulting from the presence of sulphur in numerous fuels. Such sulphur, as shown in Table III, ordinarily burns to SO_2, which will be absorbed in the flue-gas analysis along with carbon dioxide. With fuels low in sulphur the error arising from this source is small and can be safely neglected. With fuels high in sulphur and low in carbon, however, as in the case of certain middle western coals, the error may be of sufficient amount to warrant consideration.

It is entirely possible, in determining the weight of dry products of combustion per pound of fuel burned from the weight per pound of carbon, to modify the actual carbon weight as given in the fuel analysis, in order to correct for the sulphur content; and where the sulphur content is appreciable, such correction should be made.

If formula (8) represents the weight of dry products of combustion per pound of carbon burned with fuels without sulphur content, the weight of dry products per pound of fuel will be:

$$\frac{11\,CO_2 + 8O_2 + 7\,(CO + N_2)}{3\,(CO_2 + CO)} \times C. \qquad (9)$$

The first term of formula (9), *viz.*, $(11CO_2 \div [3\,(CO_2 + CO)]$ represents not only the weight of CO_2 resulting from the combustion of carbon, but includes as well the SO_2 resulting from the combustion of sulphur. If the weights of CO_2 and SO_2 resulting from the combustion of one pound of carbon and one pound of sulphur, respectively, were the same, the necessary correction, for the proper determination of the weight of dry products of combustion per pound of fuel from formula (9), could be made by simply adding the sulphur content to the carbon content of the fuel. The CO_2 resulting from the combustion of 1 lb. of carbon, however, is, from Table X, 3.667 lb., while the weight of SO_2 from 1 lb. of sulphur is 2.00 lb. The correction factor must be in the ratio of these weights, and the correct value, instead of being $(C + S)$, will be $(C + \frac{S}{1.833})$.

For fuels with a sulphur constituent, then, the weight of dry products of combustion per pound of fuel will be—

$$\frac{11\,CO_2 + 8O_2 + 7(CO + N_2)}{3(CO_2 + CO)} \times \left(C + \frac{S}{1.833}\right) \qquad (10)$$

Roughly, the error resulting from the use of formula (9), in the case of fuels containing sulphur, is 1 per cent for each 1 per cent of sulphur in the fuel. Since formula (9) is used in the computation of what is ordinarily the largest combustion loss, *viz.*, the dry chimney gas loss, the necessity for correcting for the sulphur content with high sulphur fuels is obvious.

While formula (10) may be accepted as correct for the determination of the weight of dry products of combustion per pound of any fuel, it is not to be accepted, however, without additional data in the way of fuel analysis, in the computation of total gas weights or in the computation of the amount of air supplied for combustion. The chief reason for this statement lies in the fact that practically all fuels contain a certain amount of hydrogen. The oxygen supplied for the combustion of this hydrogen does not appear in the dry flue gases and is not accounted for by formula (9), while the nitrogen which accompanied the oxygen so utilized does appear in the dry gases and in the analysis. It is not always made clear why, in spite of this fact, formula (9) can be used safely for the computation of the dry gas per pound of carbon or per pound of fuel, and a word of explanation on this feature seems advisable. The carbon content of the fuel must all appear in the dry gases in the exact amount* as in the fuel,

* Less the unconsumed C in the ash.

either as carbon dioxide or as carbon monoxide. The basis of formula (9) is, as has been shown, simply the weight relation between a known quantity of one constituent of the dry gases (carbon) and the total weight of such gases, regardless of the composition of such total weight or the sources of its constituents; and with the weight and the percentage weight of a single constituent known, the total weight is obvious.

The total weight of the products of combustion per pound of fuel obviously will be the weight of dry products per pound plus the moist products per pound from all sources.

Practically all fuels contain moisture and such moisture will appear in the products of combustion, the weight per pound of fuel appearing as the same weight in the total products. Further, most fuels have an appreciable hydrogen content; and assuming that all this hydrogen is completely burned to form water vapor, the amount of such water vapor being readily computed from the data of Table X, such weight will be a constant, regardless of the amount of air supplied for combustion. The remaining source of moisture that will appear in the products of combustion is in the moisture content of the air supplied for combustion. This amount is ordinarily small, however, and in commercial practice usually may be neglected.

The total products of combustion per pound of fuel as fired will be as follows:

Dry products per pound + moisture in fuel per pound + $9H_2$, where the weight of dry products is determined from formula (10), the values of C and S in the formula being on a fuel-as-fired basis; the moisture content of the fuel is in pounds per pound of fuel fired, and H_2 is the weight of hydrogen per pound of fuel fired. If, in refined work, more accurate results are required, the weight of water vapor in the air supplied for combustion per pound of fuel should be added. Such weight may be computed from the weight of air supplied per pound, wet and dry bulb thermometer readings, and psychrometric tables.

Air Supplied for Combustion.—Unquestionably the best method of determining the weight of air supplied, and, in fact, the only method that may be used safely for all fuels, is through the use of formula (10), giving the dry products of combustion per pound of carbon or of fuel, and, in conjunction with this formula, certain data of perfect combustion which may be obtained from Table X.

It is customary and proper to report a fuel analysis on a dry or moisture-free basis. On such a basis, where total gas weights are desired, the water vapor in the flue gases resulting from the presence of moisture in the fuel should be computed separately, and, neglecting the moisture content of such air, the results obtained are in terms of dry fuel.

If, as stated, the combustion of the hydrogen present in any fuel is complete, the water vapor content of the flue gases from this source must be a constant weight, regardless of the amount of air supplied for combustion. Obviously, then, the total weight of the products of combustion per pound of dry fuel for any amount of excess air must equal the dry products of combustion per pound, as given by formula (10), plus the constant weight of the water vapor formed in the burning of the hydrogen content. Further, the total weight of the products of combustion of the dry fuel must equal the weight of air supplied plus the weight of the fuel which is burned, and appears in the flue gases. Hence:

Dry products per pound fuel + H_2O from H_2 = dry air supplied per pound + (weight of fuel in gases);* or

Dry air supplied per pound = dry products per pound + H_2O from H_2 − (weight of fuel in gases.)

From the weight of air supplied as so determined, and the weight theoretically required, as computed from Table X or by formula (7), the amount of excess air may be readily found, as may be the ratio of air supplied to that theoretically necessary, which value, assuming complete combustion, is, in the last analysis, the true measure of the efficiency of combustion.

This method of computation of the amount of air supplied necessitates an analysis of the fuel burned and an analysis of the products of combustion. A number of formulas have been offered based only on the gas analysis, but none of these is applicable for all classes of fuel.

One such formula, however, will give reasonably accurate results with most solid and liquid fuels. This is as follows:

$$\text{Dry air supplied per pound C} = \frac{3.036\ N_2}{CO_2 + CO}, \qquad (11)$$

or

$$\text{Dry air per pound fuel} = \frac{3.036\ N_2}{CO_2 + CO} \times \left(C + \frac{S}{2.667}\right), \qquad (12)$$

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* Ex. in the case of coal (1-ash).

the constant 2.667 being the nitrogen ratio accompanying the oxygen necessary to burn 1 lb. of carbon to CO_2 and 1 lb. of sulphur to SO_2, respectively.

The error of the formula lies in the value of the constant 3.036, which will vary with the amount of excess air and the percentage of N_2 in the fuel. With solid and liquid fuels, where the nitrogen content is low, reasonably accurate results may, as stated, be obtained through the use of this formula. With gaseous fuels, however, the error may be large and the formula should not be used. With blast-furnace gas, for instance, burned with a moderate amount of excess air, due to the fact that the weight of nitrogen in the fuel itself may be practically as great as the weight in the air used for combustion, the error may be as great as 80 per cent.

The errors resulting from the proper use of flue gas analysis in the computation of combustion data are well within the error of commercial combustion work as a whole. There is, however, a real source of possible error in the conduct of analyses, and in practice there are several features that should be watched carefully where accuracy in the fuel results is desired. Assuming a proper design of analysis apparatus, the errors to be guarded against may be listed as follows:

1. Care should be taken that the sample of gas for analysis is an average sample. This is the feature which should be watched most carefully and is perhaps the most difficult of achievement. No hard and fast rules can be laid down for the methods of obtaining such an average sample, and it is largely a question of common sense. The sample should be drawn from the main body of the gases and in a location where the possibility of dilution through air infiltration is at a minimum.

2. Absorption reagents should be reasonably fresh. Each reagent is capable of absorbing a definite amount of one of the constituent gases, this amount ordinarily being expressed in terms of volume of the absorbing medium, and a check should be kept on the total absorption. Where solutions are weak and absorption is not accomplished within a relatively short time, there is a tendency to accept the absorption as complete, which results in an inaccurate analysis.

3. There is a tendency, particularly in the case of inexperienced operators, toward attempting to force the absorption. With reasonably fresh solutions, the gas should be brought into con-

tact with the absorption tubes at least twice, and oftener as the solutions become weaker. In the case of oxygen, where, through attempting to force the rapidity of the analysis, absorption is not complete, erroneous results both as to oxygen and carbon monoxide contents will be obtained, since the absorbing reagent for the latter will also absorb oxygen.

4. Analyses should be completed. Too frequently it is assumed that the carbon dioxide content alone or the carbon dioxide and oxygen contents are sufficient, but often the efficiency seemingly indicated by a high carbon dioxide content alone would be more than offset by the fact that appreciable amounts of carbon monoxide were present and not determined.

In connection with the completion of an analysis, it is perhaps well to warn the operator not to start an analysis with the fixed idea that the sum of the carbon dioxide, oxygen and carbon monoxide must total to a fixed amount. This sum, as stated, will vary with different classes of fuel and to an extent with different fuels of the same class.

COMBUSTION LOSSES

With the foregoing methods of computing combustion data available, it is possible to consider the losses which occur in the burning of any fuel. The results of the computation of such losses constitute a "heat balance" which indicates the distribution of the losses. Certain of these losses are not, strictly speaking, combustion losses, though it is customary to consider all losses together.

In the following, where the losses involve the heating of water, water vapor or air above the temperature of the atmosphere, only the initial and final temperatures need be considered. For example, in a boiler furnace, the moisture content of the fuel and the air supplied for combustion must be heated initially to the furnace temperature. Inasmuch as a portion of the heat so expended is regained in absorption by the boiler in the passage of the gases over the heating surfaces, however, only the final temperature of the gas leaving the boiler need be considered in computing the loss due to heating these constituents above atmosphere, regardless of any intermediate temperatures that may have been attained.

Combustion losses, together with the methods of their computation are the following:

1. Loss due to the moisture contained in the fuel.

All the moisture in the fuel must be heated from atmospheric temperature (or from the temperature of the fuel where this is above that at atmosphere) to 212°F., the temperature at which steam is formed, assuming atmospheric pressure, and the steam so formed must be heated to the temperature of the furnace gases.

The B.t.u. loss from this source per pound of fuel may be expressed, as follows:

$$\text{Per cent moisture} \times [(212 - t) + 970.4 + 0.48\,(T - 212)], \quad (12)$$

where t = temperature of the atmosphere or fuel,

T = temperature of the escaping gases,

970.4 = latent heat of evaporation at atmospheric pressure, and

0.48 = mean specific heat of superheated steam at atmospheric pressure. (In reality this value will vary slightly with different values of T, but the variation is small and 0.48 may be taken as representing the value for ordinary exit gas temperatures.)

In the case of gaseous fuels introduced into the furnace, the moisture content already exists as vapor. The temperature of this vapor is the same as that of the gas with which it is mixed, but its partial pressure is below that corresponding to such temperature, except where the gas is saturated, a condition which rarely occurs. Such water vapor, then, existing at a temperature above saturation, or above the temperature corresponding to its partial pressure, is in reality superheated steam; and in increasing its temperature to that of the escaping gases the question of the expenditure of heat in changing its condition, *i.e.*, latent heat expenditure, is not involved.

The loss due to the moisture content of gaseous fuels will be expressed thus:

$$\text{Per cent moisture } 0.48\ (T - t). \quad (13)$$

Where the gaseous fuel is introduced into the furnace at or near atmospheric temperatures, the specific heat of the water vapor content will be considerably lower than 0.48. The use of this value, however, as the mean specific heat over the range $t - T$ will lead to a negligible error only.

2. Loss due to moisture formed in the burning of hydrogen.

From Table X each pound of hydrogen burned will result in the formation of 9 pounds of water vapor. This moisture must be heated, as in the case of the moisture in the fuel, and the loss may be expressed as follows:

$$\text{Per cent. } H_2 \times 9\,[(212 - t) + 970.4 + 0.48\,(T - 212)] \qquad (14)$$

In the case of hydrogen, since water is an actual product of combustion, the latent heat must be taken into consideration, regardless of the fact that the moisture appears in the products of combustion as water vapor, and whether the fuel is solid, liquid or gaseous.

3. Loss due to moisture in the air.

The weight of water vapor per pound of dry air may be determined from readings of the wet and dry bulb thermometers and a set of psychrometric tables. This weight times the weight of dry air supplied per pound of fuel, as determined by the methods which have been indicated, will give the total moisture in the air supplied per pound of fuel (W). Since this moisture is already in the form of water vapor, as in the case of the moisture content of gaseous fuels, the question of the expenditure of heat in changing its condition is not involved and the loss from this source will be as follows:

$$W \times 0.48 \times (T - t) \qquad (15)$$

4. Loss due to heat carried away in the dry chimney gases.

The weight of gas per pound of fuel burned (W) may be computed by the methods indicated. In the case of solid fuels, when the weight of dry gas per pound of carbon as given by formula (10) is multiplied by the carbon content of the fuel, the proper value of the carbon for use is the percentage of carbon actually burned and appearing in the flue gases, *i.e.*, the carbon content corrected for any unconsumed carbon in the ash and refuse.

The heat lost in the dry chimney gases, then, is measured by this weight of gas (W) and the difference between the temperature of the escaping gases and that of the atmosphere. It may be expressed thus:

$$W(T - t)0.24, \qquad (16)$$

where 0.24 is taken as the mean specific heat of the gas between these temperature limits. Since this specific heat will vary with the temperature of the escaping gases and with their composition, it would be well to compute its value where the most accurate results are desired. The value 0.24, though probably somewhat low, is, however, ordinarily accepted.

5. Loss due to the incomplete combustion of carbon. This loss may be expressed as follows:

$$\frac{CO}{CO_2 + CO} \times C \times 10{,}160, \qquad (17)$$

in which C is the weight of carbon which is burned and appears in the flue gases, *i.e.*, corrected for solid fuels, as in the case of the preceding loss, for such unconsumed carbon as appears in the ash. The constant 10,160 represents the number of heat units generated in burning one pound of carbon in carbon monoxide to carbon dioxide.

6. Loss due to carbon appearing in unconsumed refuse. This loss may ordinarily be determined only in the case of solid fuels. It is expressed as follows:

$$\frac{c \times C}{100} \times 14{,}600, \qquad (18)$$

where

c = weight of ash per pound of fuel,
C = percentage of unconsumed combustible matter in the ash, and
$c \times C$ = weight of unconsumed carbon in terms of total carbon per pound of fuel.

The unconsumed combustible matter in the refuse is assumed to be entirely carbon, for which 14,600 B.t.u. per pound is taken as the approximate heat value. This assumption will give rise to an error which is negligible.

7. Radiation and unaccounted losses.

These losses, which are either impossible or impracticable to measure, include:

(*a*) Radiation loss, which, in terms of percentage, will vary with the size and the condition of the furnace and like factors.

(*b*) Losses due to the unburned volatile hydrocarbons.

(*c*) Loss due to the combination of carbon and moisture, with the consequent formation of hydrogen ($C + H_2O = CO + 2H$), which may or may not be burned. This action may occur when moist fuel is thrown on an incandescent fuel bed.

(*d*) Other losses not accounted for above.

The total of the losses under item seven is taken as the difference between 100 per cent and the boiler efficiency plus the sum of the six losses as computed.

Of the losses which may be computed as above, the first, second and third are only to an extent controllable. Since the moisture content of all fuels and of air, and the hydrogen content of most fuels, must be accepted as found, the only manner in which these losses may be kept at a minimum for a given fuel is by the reduction of the exit gas temperature to the lowest possible or practicable figure. Assuming proper combustion, the temperature of the gases escaping up the stack is a function of the efficiency of heat absorption by the medium to be heated, *e.g.*, of boiler design, heating furnace, kiln design, etc., the minimum possible escaping gas temperature, of course, being dependent upon the nature of the apparatus involved and the purposes for which the heat is generated. From this aspect the matter is rather one of design than of combustion proper. If, on the other hand, proper design of boiler, furnace, or the like, is assumed, these three losses are controllable to the extent that exit gas temperatures are controllable.

The fourth loss is more truly a combustion loss though, since it is affected by exit gas temperatures, this too is dependent on design of apparatus. Obviously, with a given fuel, and for a given exit gas temperature, the greater the gas weight, *i.e.*, the greater the excess air, the greater the loss of heat in the chimney gases. This loss is kept at a minimum when complete combustion is made to approach perfect combustion.

The fifth loss is entirely a combustion loss, and is to be prevented only by the admission of sufficient air for complete combustion and in a manner that such complete combustion is assured. In endeavoring to bring about such conditions, the tendency is toward the introduction of too great an amount of air, in which case the carbon monoxide loss will be reduced or prevented at the expense of a loss resulting from the fourth source. It is to be remembered that, while the absence of carbon monoxide in the flue gases indicates complete combustion, it does not of necessity indicate efficient combustion.

The sixth loss, which can only be determined with solid fuels, is not properly speaking a combustion loss and is the result of the physical factors entering into the design of furnaces, stokers or grates, and in the operation of the apparatus. Assuming the best of design, this loss is minimized through proper operation.

It will be noted from the foregoing that the two main factors upon which the extent of all combustion losses depend are the amount of air supplied for combustion and the temperature of the gases leaving the apparatus. The factor of air supply can, to an extent, be controlled; but if we assume the ability of the primary apparatus to absorb heat efficiently within the limits for which it is designed, the factor of escaping gas temperature can only be controlled to the extent that it is dependent upon air supply.

The stack loss due to excess air will increase with such an excess, not only because a greater amount of air than that actually required for combustion must be heated from atmospheric temperature to that of the escaping gases, but also because the ultimate temperature will, within ordinary limits, be higher as the amount of excess is increased, the two factors combining to increase the possible loss under the fourth item above.

The effect of incomplete combustion in the furnace may be either to reduce or increase exit gas temperatures.

If the combustion of a given fuel is not completed in the furnace before the combustible gases come into contact with the heat absorbing medium, the temperature evolved in the furnace, and hence the temperature of the products of combustion, will be less than if such combustion were complete. If such unconsumed or partially consumed gases pass up the stack without encountering somewhere in the apparatus sufficient additional oxygen for the completion of combustion, or temperatures under which combination resulting in further combustion will take place, the result on the ultimate flue-gas temperature would be to reduce it below what it would be if combustion had been complete in the furnace. If, on the other hand, these partially consumed gases encounter at some point in their passage through the primary apparatus sufficient oxygen for continued combustion with a temperature above the ignition point, such combustion will occur. In boiler practice this is known as *delayed* or *secondary combustion*, and ordinarily will take place at such a point within the boiler setting as to increase appreciably the temperature of the exit gases above that which would result from complete combustion in the furnace.

SMOKE

Though there is perhaps no phase of combustion that has been discussed so fully as that which results in the production of smoke, the common understanding of the loss from this source is at best vague and based in part at least on misconception. For this reason, a brief consideration of smoke is included here, regardless of the amount of data on the subject available elsewhere.*

Of the numerous and frequently unsatisfactory definitions of smoke that have been offered, that of the Chicago Association of Commerce Committee in its report on "Smoke Abatement and the Electrification of Railway Terminals in Chicago" is perhaps the best. This report defines smoke as "the gaseous and solid products of combustion, visible and invisible, including . . . mineral and other substances carried into the atmosphere with the products of combustion."

From the standpoint of combustion loss it is necessary to lay stress on the term "visible and invisible." The common conception of the extent of loss is based on the visible smoke, and such conception is so general that practically all, if not all, smoke ordinances are based on visibility, density or color of escaping stack gases. As a matter of fact, the color of smoke, which is imparted to the gases by particles of carbon, cannot be taken as an indication of the stack loss. The invisible or practically colorless gases issuing from a stack may represent a combustion loss many times as great as that due to the actual carbon present in the gases, and but a small amount of such carbon is sufficient to give color to large volumes of invisible gases which may or may not represent direct combustion losses. A certain amount of color also may be given to the gases by particles of flocculent ash and mineral matter, neither of which represents a combustion loss. The amount of such material in the escaping gases may be considerable where stokers of the forced draft type are used and heavy overloads are carried.

The carbon or soot particles in smoke from solid fuels is not due to the incomplete combustion of the fixed carbon content of the fuel. They result rather from the non-combustion or incomplete combustion of the volatile and heavy hydrocarbon constituents, and it is the wholly or partially incomplete combustion of these constituents that causes smoke from all fuels solid, liquid or gaseous.

If the volatile hydrocarbons are not consumed in the furnace, and there is no secondary combustion, there will, of course, be a direct loss resulting from the non-combustion of these constitu-

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*See, in particular, the *Bulletins* of the Smoke Investigation of the Mellon Institute of Industrial Research of the University of Pittsburgh.

ents. While certain of these unconsumed gases may appear as visible smoke, the loss from this source can not be measured with the ordinary flue gas analysis apparatus, and must, of necessity, be included with the unaccounted losses.

Where the combustion of the hydrocarbon constituents is incomplete, a portion of the carbon component ordinarily appears as soot particles in the smoke. In the burning of hydrocarbons, the hydrogen constituent unites with oxygen before the carbon; for example, in the case of ethylene (C_2H_4):

$$C_2H_4 + 2O = 2H_2O + 2C.$$

If, after the hydrogen is "satisfied," there is sufficient oxygen present with which that carbon component may unite, and temperature conditions are right, such combinations will take place and combustion will be complete. If, on the other hand, sufficient oxygen is not present, or if the temperature is reduced below the combining temperature of carbon and oxygen, regardless of the amount of oxygen present, the carbon will pass off unconsumed as soot.

The direct loss from unconsumed carbon passing off in this manner is probably rarely in excess of one per cent. of the total fuel burned, even in the case of the densest smoke. The loss due to unconsumed or partially consumed volatile hydrocarbons, on the other hand, though not indicated by the appearance of the gases issuing from a stack, may represent a very appreciable percentage of the total fuel fired.

In boiler practice, while the loss represented by the visible constituents of smoke leaving a chimney ordinarily may be considered negligible, there is a loss due to the presence of unconsumed carbon and tarry hydrocarbons in the products of combustion which, while not a direct combustion loss, may result in a much greater loss in efficiency than that due to visible smoke. These constituents adhere to the boiler heating surfaces, and, acting as an insulating layer, greatly reduce the heat absorbing ability of such surfaces.

From the foregoing it is evident that the stack losses indicated by smoke, whether visible or invisible, result almost entirely from improper combustion. Assuming a furnace of proper design and fuel burning apparatus of the best, there will be no objectionable smoke where there is good combustion. On the other hand, a smokeless chimney is not necessarily indicative of proper or even of good combustion. Large quantities of excess air in diluting the products of combustion naturally tend toward a smokeless stack, but the possible combustion losses corresponding to such an excess air supply have been shown.

GENERAL CONCLUSIONS

In view of the great number of factors involved in the combustion of any fuel, and the great variation in the characteristics, not only of different classes of fuel, but of different fuels of the same class, it is obvious that the specific requirements for the proper combustion of an individual fuel must be considered as a distinct problem. It is possible, however, from the foregoing, to draw certain general conclusions as to the combustion requirements of any fuel, whether solid, liquid or gaseous; and since such conclusions form the basis of the design of all combustion apparatus, they are worthy of careful note.

These general requirements of proper combustion may be summarized as follows:

1. The admission of an air supply such as will assure sufficient oxygen for complete combustion.

2. Since complete combustion is not of necessity efficient combustion, it must be secured without permitting the dilution of the products of combustion with excess air. It follows, then, that—

3. The air supply should be admitted at the proper time and in such a manner that the oxygen of the air comes into free and intimate contact with the combustible substances of the fuel. In the case of solid fuels this means not only into contact with the solid particles of the oxidizable substances, but also with the combustible gases as they are distilled from the fuel.

4. The gases must be maintained at a temperature at or above their ignition points until combustion is complete. Theoretically, as has been indicated, the most efficient combustion is that resulting in the maximum temperature possible. In practice, there are frequently factors which, from the standpoint of operating at commercial efficiency, make it advisable to keep furnace temperatures somewhat below those which could be obtained were this the sole factor involved.

5. An additional requirement, which has to do with the physical rather than the chemical aspect of combustion, is that proper provision must be made for the expansion of gases during the period of their combustion.

In considering combustion, it is necessary, though perhaps difficult for the average operator, to distinguish between the purely chemical changes that accompany oxidation and the purely physical aspect of the later transformation of the heat energy evolved in the passage of the products of combustion through the apparatus designed for heat absorption. The efficiency of combustion is thus independent of the heat absorbing ability of the primary apparatus, and in the requirements of proper combustion just summarized such ability is either assumed or neglected.

From the general conclusions drawn it would seem perhaps a simple matter to meet the requirements of proper combustion. Unfortunately, however, such is not the case and it is, as stated heretofore, the physical and mechanical details encountered in attempting to fulfill such requirements that render the problem of proper combustion difficult. Assuming proper furnace form and adequate combustion temperatures, the problem is solely one of air admission and admixture. The factors entering into the problem and the methods used to bring about the desired results are varied so widely for different fuels, that it is necessary, as stated, to consider each class of fuel specifically for any but the most general statements.

CHAPTER III

THE TECHNOLOGY OF COKE

BY

F. W. SPERR, JR.*

COKE AND ITS RELATION TO COAL

Coke may be defined as the coherent cellular residue of the destructive distillation of coal at high temperatures.† Not all classes of coals are capable of producing coke and simple heating does not in itself suffice for making coke even from what are classed as coking coals. The study of what constitutes the coking property of a coking coal and the investigation of the process of coke formation are of prime importance in modern industry.

If we examine the behavior of different coals on heating, we observe certain characteristic differences that appear to be related in a very approximate way to the usual classification of the coals, as anthracite, bituminous and lignite. Heated rapidly to a high temperature (over 900°C.), out of contact with the air, the anthracites and semianthracites evolve a small amount of gas but do not appreciably alter in shape. The lignites rapidly evolve large quantities of volatile matter and the particles of solid residue shrink and crack considerably, but retain to a large extent their original shape and show no tendency to cohere. A typical rich bituminous coal on the other hand rapidly fuses; the fused mass intumesces violently with a copious evolution of volatile matter and then hardens to a bright gray, strongly coherent, porous mass which shows none of the physical proper-

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* Chief Chemist, The Koppers Company, Pittsburgh, Pa.; and Advisory Fellow, Multiple Industrial Fellowship on Coke Technology, Mellon Institute of Industrial Research of the University of Pittsburgh.

† The same term is applied to the final residues of distillation of coal-tar pitch, petroleum, asphalt and other bituminous materials.

These cokes, known individually as pitch coke, petroleum coke, etc., are of value in the electrochemical industry; but are of minor importance in comparison with coke proper which is derived from coal.

ties of the original coal and which is, in fact, the material that we call coke. This characteristic fusion occurs first between 300° and 400°C.; and "if a coarsely powdered sample of the coal becomes pasty or semifluid at this temperature, it is a strong inference that the coal will coke on carbonization."

Not all bituminous coals, however, form coke when thus heated. Some lose their original form and produce a peculiar sintered mass, like an agglomeration of small pebbles, soft and rather loosely coherent. Naturally there are all sorts of gradations in behavior between the anthracite and bituminous coals on the one hand and the bituminous coals and the lignites on the other hand. The semibituminous coals as a rule make good coke* but the subbituminous coals do not.

The modern view, to the expression of which chief credit belongs to Vivian B. Lewes, is that these differences in behavior on heating are to be attributed to differences in the humus and resin constituents of the various coals. That resinic substances play a very important part in the composition of coal in general was realized only a few years ago, but has received strong corroboration from the work of many investigators, notably Thiessen and White of the United States Bureau of Mines and Geological Survey, respectively.

According to Thiessen,[8]† coal is composed chiefly of residue consisting of the most resistant components of plants of which resins, resin waxes, waxes and higher fats or the derivatives of the compounds comprising these are the most important. He has disproved the "algal" theory of Bertrand and Renault, according to which certain gelesic algæ were supposed to play an important part in the origin of coal and in its coking properties. White was for a time disposed to accept the algal theory or Potonie's modification of it, which introduced the conception that the properties of coal were due to two essential and radically different classes of constituents, *viz.*, sapropelic and humic materials, the "sapropelites" including such aquatic organisms as the algæ. White's studies of the effect of oxygen in coal,[10] in which he attributed to bituminized algal matter the properties of fusibility and coking, gave some interesting information that

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* See Thiessen's excellent memoir on the microscopic study of coal (*U. S. Bureau of Mines Bull.* **38, 1913**) for a summary of work done on this subject.

† See the *list of references* appended to this Chapter.

may be readily reconciled to the resin theory, of which he is now a strong supporter.

"The period of marked alteration[9] and reduction (carbonization) of the normal megascopic resins in the coals of the Cretaceous and Tertiary age seem in general to coincide with that point in the devolatilization of the fuels which leads (other things being equal) to the development of the qualities essential to the production of high standard commercial coke. . . . . The typical coking quality, once developed, continues until the coal is carried approximately to the semianthracite rank, or, apparently, as long as sufficient volatile carbon and hydrogen remain in the fuel."

White and Thiessen are not decided as to what is the nature of the constituents other than the substances of resinic and waxy origin. Lewes regards such other constituents as essentially humic,* and has developed the theory of the coking property as follows:

> "The humus bodies during carbonization yield a large proportion of the gaseous products, and under the influence of heat show no sign of melting, but begin to break up at about 300°C., the decomposition becoming more rapid as the temperature rises. Water distils over in the early stages, the tar is thin and poor in quantity, and the gases up to 600°C. consist of H, CH_4, and CO_2 with smaller quantities of CO and traces of other saturated hydrocarbons, the decomposition can be completed below 600°C.; but if the temperature is run up to 1,000°C., the CO_2 is reduced in quantity by the action on it of the red-hot carbon and CO increases correspondingly, whilst H, and CH_4 are still evolved.
>
> "The decomposition of the humus is also largely affected by the rate of heating, if slowly heated, a large proportion of the oxygen is given off in combination with hydrogen as H_2O vapor, whilst if quickly raised in temperature more combines with C to form CO_2 and CO.
>
> "The residue shows no sign of caking, whilst, like the natural formed residue—mother of coal—it requires a large proportion of cementing material to make the particles cohere.
>
> "The resin bodies and hydrocarbons which form the cementing portion in the coal melt between 300°C. and 320°C. and if a coarsely powdered sample of the coal becomes pasty or semi-fluid at this temperature, it is a strong inference that the coal will coke on carbonization, a fact noted by Anderson and which I have found very useful in practice

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* Stopes and Wheeler[45] point out that some confusion has arisen from the words humic and humus as applied to the constituents of coal. Lewes uses these terms as signifying the degradation products of cellulose.

as a rough test. About these temperatures also the resin bodies and hydrocarbons begin to decompose.

"The resin bodies, at low temperature yield saturated hydrocarbons, unsaturated, chiefly hexahydrides or naphthenes, together with some oxygenated compounds, whilst the hydrocarbons yield paraffins and liquid products, all these primary constituents undergoing further decomposition at slightly higher temperatures. The liquids so produced begin to distil out as tar vapors and hydrocarbon gases, and leave behind with the residium pitch, which at 500°C. forms a mass already well coked together if the residium from the humus is not too large in quantity. The coke formed at this temperature is, however, soft but if the heat be now raised to 1,000°C., the pitch residue undergoes further decomposition yielding gas and leaving carbon which binds the mass into a hard coke."

Relation of Coking Property to Analysis.—It would, of course, be of the utmost importance if we could discover some relation that would enable us to predict from the results of a proximate or an ultimate analysis of a sample whether the coal represented would make good coke. However, hundreds of investigations made along this line have uniformly shown that such analyses are of value only in establishing a preliminary approximate prognosis of the coking property; the actual character of the coke from a given coal can only be determined by actually making it.

The ratio of fixed carbon to volatile matter, as obtained by an ordinary proximate analysis, is of some value if the geological relations of the coal are well known and the district from which it is obtained has been well studied, but any deductions made from this ratio become exceedingly unsafe if applied in the same way to coals from a new field. Thus, a coal of 33 per cent. volatile matter and 60 per cent fixed carbon from western Pennsylvania may be confidently expected to have good coking properties, while a coal of the same proximate analysis from southern Illinois may make a very poor coke. These analyses are so easily and quickly made that there is great temptation to over use them.

The results of ultimate analyses are of broader application. The differences in coking quality between coals of similar proximate analysis appear to be usually related to differences in their oxygen content. Appreciation of this led many investigators to consider the coking property related to the percentage of available hydrogen. This, although possibly a truer indication than the ratio of fixed carbon to volatile matter, is, like the latter, of local application only. White's studies of over three hundred coals[10] show that, while practically all the coals with an available hydrogen of 3.80 per cent or more will coke well unless they are too high in fixed carbon, some good cokes result from fuels with less than 3.50 per cent. Several of the tests show cokes from coals with as low as 3.20 per cent available hydrogen. The method also breaks down in the highest semi-bituminous coals. The loss in volatile in most of the coals of that category leads to a falling off in the available hydrogen. However, on account of the relatively more rapid oxygen loss in the higher coals, the available hydrogen percentages sometimes persist after the coal refuses to coke.

In view of the well established effect of oxygen in injuring or destroying the coking property, it seems logical to endeavor to determine some relation based more directly on the percentage of this element. White considers the hydrogen-oxygen ratio as the best index.

> "A review of the wide fluctuations in the H : O ratios, together with the annotations as to coking, strongly indicates, so far as the tests have been made or the information is at hand, that, below the highest of the semibituminous coals which are approaching anthracitization, those coals with a H : O ratio (percentage) of 59 or more, with but one or two exceptions, make coke by the ordinary commercial process. Nearly all those below 59 and above 55, so far as tested, make a coke, and among those ranging down to a ratio of 50 a large percentage coke, while one or two of the tested coals coke at a slightly lower ratio. It would seem, however, that the cokes made from those coals with a H : O ratio less than 55 are usually very poor and apt to be brittle and dark.
>
> "It appears, therefore, that among coals which are not too far devolatilized practically all that are sufficiently bituminized—that is, have a H:O ratio of 59 or over—are almost certain to possess the coking fusibility, and that coke of good quality may usually be expected from coal with a ratio as low as 55, while very poor results may be obtained when the ratio is as low as 50. The best cokes obtained by the ordinary process are made from coals having a ratio of 60 or over."

Although the H : O ratio may be a useful indication as to whether or not a coal will make coke and may possibly give a general indication of the approximate quality of the coke, it must be used with discretion until studies of it have been further developed, especially with reference to coking in by-product ovens. It should be noted that most of White's conclusions were based on observations of beehive practice; they were the best available at the time his studies were made, but it is to be hoped that we may soon have a similar investigation of the behavior of a large variety of coals in the by-product oven.

Having set forth the theory that the coking quality of coal depends upon its content of resinic substances, it remains for us to determine what part these play in the process of coke formation. In doing this, it will be necessary for us to examine more thoroughly the behavior of coal on heating.

Effect of Heating on Coal.—So far, we have studied only one mode of heating, *viz.*, rapid heating to a high temperature. Different results are obtained by varying the rate of heating and the final temperature. Heating to 450°C. gives, even in the case of the best coking coals, only weak friable cokes.[3] If, after heating to this temperature, the residue is pulverized, the particles cannot be made to cohere by any process of heating whatsoever; furthermore, by a sufficiently slow rate of heating a very soft coke will be formed even at a final temperature of 900°C. or more. This slow rate of heating considerably increases the percentage yield of coke.[4]

O. Rau heated a good coking Westphalian coal of 79.9 per cent coke yield in nitrogen with careful exclusion of oxygen. At 200°C., the coal lost only 0.81 per cent of its weight in 24 hr., and, when afterwards coked in the usual manner, gave a good coke (81.69 per cent), which was only a trifle more friable than that from the fresh coal. When the coal was heated 24 hr. longer in nitrogen at 300°C. it lost 0.54 per cent more in weight and then gave 82.14 per cent of a partially sintered, very friable coke. The same coal in a fresh condition, when heated 22 hr. at 210° in the air, increased 5.27 per cent in weight and then gave 64.72 per cent of a pulverulent coke (all calculated to an ash-free basis).

Parr's work on the distillation of Illinois coals at low temperatures showed that for this class of coals an essential condition for the formation of a good coke is exclusion of oxygen from the retort in which the coking takes place. Heated at a temperature of 400° to 500°C. in an atmosphere of superheated steam, two such coals gave coke of good quality.

O. Boudouard[5] found that the coking property was destroyed by heating for 105 hr. in the air at 100°C. He observed a production of humic acid as a result of such heating. The coking property was also destroyed by concentrated nitric and sulphuric acids, while concentrated hydrochloric acid had no effect.*

The destruction of the coking property by oxidation is explained by the hypothesis that the resinic substances, which act as binding agents in the coking process, are decomposed under this condition. As Parr has pointed out, the temperature at which decomposition of the fusible substances occurs must be above their melting point. If it is lower, no coke will be formed. Every observation of the effect of oxidation confirms the belief that it has the effect of altering or destroying the binding material.

Prolonged heating at a low temperature may have the same effect as oxidation, but this seems hardly likely because, on this assumption, the conditions of geological metamorphism, to which all coals of the higher rank have been exposed, would in themselves tend to destroy instead of promote the coking property. Rau's explanation is more reasonable. No coal will coke if heated sufficiently slowly, or if maintained at a low temperature for a sufficient length of time, simply because the resulting decomposable tarry constituents then have time to pass off without decomposition; if, on the contrary, the interval between 200° and 300°C. is traversed quickly enough, the tarry constituents formed are overtaken within the mass of coal by their temperature of decomposition and coking takes place. The coking results from decomposition of the tarry constituents within the mass of coal, with separation of carbon, or substances rich in carbon. The higher the oxygen content of the tar, the less high-carbon products will it give; hence oxidized coals and coals originally high in oxygen do not coke. This is supported by Christie's observation† that the coking process stands in close relation with the formation of a thick tar.

The tarry matters, produced by decomposition of the resinic constituents of the coal, when heated alone leave a porous residue which is soft and friable.[12] Since this cementing material is in itself structurally weak, its function should be merely that of a binder, to hold together the harder particles of carbon. This is good analogy with well known practice in the use of cements

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* See also ref. 12 for further data on effect of oxidation or weathering.

† *Diplomarbiet-Aachen,* **1905.**

in general. On this basis the strongest coke would be that containing the minimum cementing material consistent with a good bonding effect. The practice of mixing coals for production of coke of the best quality is based largely on these principles. Coals producing an excess of the binding material are mixed with those deficient in such material. Parr was able to make coke of superior quality by mixing Illinois coals rich in binding material with large quantities (up to 100 per cent) of pulverized residues of low temperature distillation of the same coals.

Explanation of Coke Formation.—If, now, slow heating has a tendency to destroy the coking property how is it that we are able to make coke at all from large masses of coal in beehive or by-product ovens? The explanation of the process of coking coal *en masse* is a most ingenious one, first proposed by Hilgenstock,[13] and confirmed by the work of all subsequent investigators.

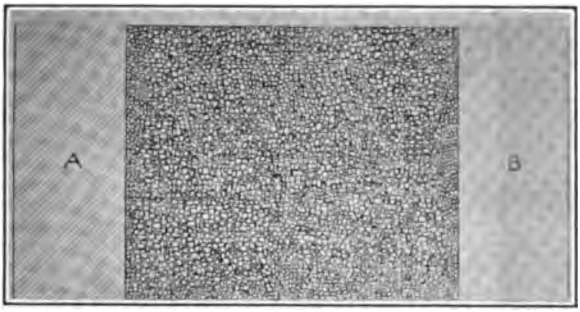

FIG. 3.—Section across by-product coke-ovens immediately after charging.

In brief, it presupposes the formation and gradual advance through the mass of coal, of a zone of fused material which is impervious to gases and acts as a virtual screen protecting the coal from premature decomposition.

Let us consider how the explanation applies to the operation of coking in a by-product oven. Let Fig. 3. represent a section across such an oven immediately after the charge of coal is introduced. The layer of coal next to each wall (*A*) and (*B*) is very rapidly heated and at the temperature of 300 to 400°C. becomes soft and pasty. The pasty mass is for a while in a state of violent ebullition, due to the rapid expulsion of its volatile matter, and then rapidly solidifies, the indurated residue retaining the vesicular form and structure of the pasty, foaming stage.

The adjacent layer toward the interior has, in the meantime, reached the pasty stage, the fusion being assisted by the penetration of some of the soft material forced over from the outer layer.

The gases and vapors follow always the line of least resistance and pass through the porous outer layer and up along the wall of the oven, instead of forcing their way through the viscous inner portion of the fused layer and then through the mass of coal. In passing through the highly heated porous layer, the hydrocarbons undergo a partial secondary decomposition, depositing part of their carbon on the cellular surfaces just formed, thus building up and strengthening the coke. The coking process is thus to be conceived as involving the formation of a fused zone and the gradual advance of this zone toward the center of the oven, the evolved gases and vapors depositing part of their carbon in the vesicular mass left as the zone progresses. The condition of the material in the oven when the coking has fairly well advanced may be represented by Fig. 4. (*C*) is the portion already coked; (*D*) is the fused zone merging into an adjacent zone; (*E*) which, being in a state of incipient fusion, is more viscous; (*F*) is the uncoked coal.

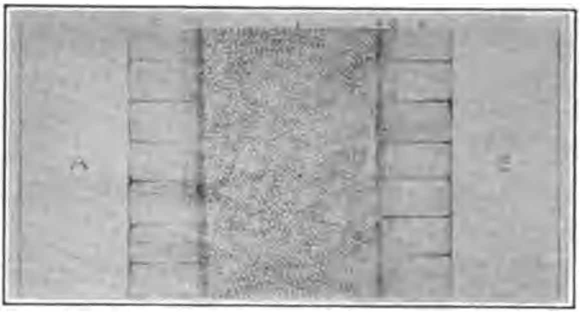

FIG. 4.—Section across oven, showing progress of coking.

The actual thickness of the fused zone is probably not over ½ in. The drop of temperature across this narrow zone is very great and the interior of the oven remains comparatively cool even at an advanced stage in the coking process. Experiments on Koppers ovens of 18¼ in. mean width, operating on approximately 18 hr. coking time, show that, during the first hour, the temperature in the middle of the oven is about 250°C. This initial temperature, which is due to a rapid permeation of hot gases while the fused zone is in process of formation, drops to about 100°C. and remains at this point until the coking period is half completed, then it rises to about 1,000°C. at the end of the coking period.

As the coking progresses, cracks or joints develop perpendicular to the walls of the oven, thus determining the blocks of coke as they are eventually formed when the oven is discharged. These cracks form avenues of escape for a large percentage of the gases, hence the amount of deposited carbon is greater in proportion on the surfaces of the blocks than in the interior. Eventually, the two zones merge at the center of the oven (Fig. 5) and, with the practically complete expulsion of the last of the volatile matter, the coking process is finished. There is always a distinct parting in the center of the oven, so that the length of the blocks is equivalent to about half the width of the oven.

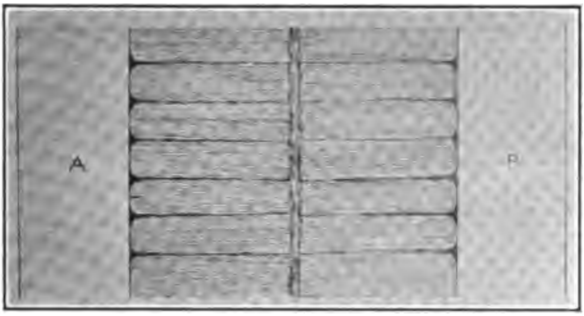

Fig. 5.—Section across oven, showing coking completed.

The rate of advance of the two zones toward the center of the oven depends, principally, upon the temperature of the walls (*A*) and (*B*). With ovens 18 in. wide and wall temperatures of about 1,000°C., the average rate is about ½ in. per hour. The initial rate is, however, much more rapid than this, and decreases as the center of the oven is approached. If the walls are heated unequally, the center parting is moved toward the wall which has the lower temperature. Ovens occasionally have been coked from one side only, and produce coke in blocks whose length is nearly equal to the full width of the oven, and which resembles beehive coke in size and appearance. In the beehive oven, the heating proceeds from the top and the fused zone must be conceived as moving slowly downward. The duration of the coking operation in the beehive oven is much longer than in the by-product oven, a charge 24 in. deep being carbonized in from 48 to 72 hr. in the former; while in the modern by-product oven charges of 18 in. thickness are frequently carbonized in 16 hr. The slow passage of the gases over the surfaces of the coke in a beehive oven favors the decomposition of the hydrocarbons, the carbon of which is deposited as a thick, glossy skin over the surfaces of fracture.

Characteristics of By-product Coke.—Particular attention will now be given to the appearance and structure of coke from the by-product oven. Figure 6 shows views of the material as it appears just after the quenching operation. A few characteristic blocks are shown in Fig. 7, in which the three smaller pieces represent cross-sections. The end of the block (Fig. 8) that was originally adjacent to the wall of the oven may always be distinguished by its cauliflower-like appearance and dense layers of deposited carbon. This end will be designated as the wall end and the other extremity will be called the center end. The structure of the coke toward the center end is always more open and occasionally is somewhat spongy. The shape of the coke is quite characteristic, depending upon the coal from which

Fig. 6.—View of typical by-product coke on wharf just after quenching.

it has been produced and also to a considerable extent upon the amount of heat treatment. In technical nomenclature, it is classed as either "blocky" or "fingery." Some typically fingery coke is shown in Fig. 9. As a rule, coke from coals of over 30 per cent volatile matter is apt to have a fingery tendency and this becomes highly pronounced if the coal has a high oxygen content. By coking such coals very slowly at temperatures some-

FIG. 7.—Blocks of by-product coke.

FIG. 8.—Wall end of a piece of by-product coke.

what lower than used in ordinary practice, the fingery tendency may be disguised or, in many cases, entirely eliminated. If the tendency is disguised, the product actually will appear to form large massive blocks, but these blocks, if closely examined, will be found to be bundles of slender pieces more or less firmly cemented together. However, if the heat treatment is very carefully regulated during the coking process—especially in ovens specially designed and adapted to this particular type of coals—genuine, firm, blocky coke may be made from many coals usually regarded as producing only the fingery variety.

FIG. 9.—Fingery coke on wharf.

The size of the blocks is affected to a certain extent by almost all the conditions pertaining to the manufacture of coke. The length is, of course, dependent upon the width of the oven, the average being, on account of shrinkage, a little less than half the width of the oven. The blocks from the top of the oven are usually considerably shorter than those from the bottom. Overcoking and high temperatures tend to produce small sized coke.

Coming now to an examination of the natural surfaces of the blocks, we may, in the first place, disregard the color as being relatively unimportant. It depends largely upon the method of quenching,—the use of large amounts of water causing a dark color, while, with the careful use of a minimum quantity of water, a light-gray color can always be preserved. The majority of cokes produced from the standard coking coals rich in hydrocarbon production and low in oxygen have close-textured, even surfaces, with possibly a few narrow transverse zones of slightly larger cell openings interspersed between the two extremities. Many cokes from coals of the Connellsville (Pa.) type show the same silvery, glossy skin that used to be so much prized in beehive coke. This is probably indicative of a very heavy deposit of carbon, especially favored by slow and uniform evolution of a very rich gas.

Other cokes are characterized by a peculiar shaggy appearance, as if they were covered with blotches of dark moss. This appearance usually is found in cokes produced from mixtures of eastern coking coals with the somewhat more highly oxygenated coals of the Central field. Oddly enough, both types of coal usually make smooth coke, if carbonized separately.

Certain cokes present transverse pebbly seams—usually not more than two or three. These seams are very narrow and quite coherent and may be shown to be composed of small globules of quite pure carbon with no apparent cellular structure. This phenomenon again appears to be characteristic of the more highly oxygenated coals.

The surfaces always show more or less transverse longitudinal cracks, significantly at right angles, either parallel or perpendicular to the wall of the oven. Naturally, these are an element of weakness and their presence to an excessive degree is one of the surest "first-hand" indications of an inferior grade of coke that we have. The amount of fracturing can be controlled to a surprising extent by proper methods of heat treatment.

By breaking a piece of coke and examining the fresh surfaces, we find revealed the cellular structure that is characteristic of all cokes and which cannot be seen in its true development simply by inspecting the dense natural surfaces. No definition of coke is complete that does not take this cellular structure into account.

The usual way, and the easiest, to examine the cell structure is to break a piece of coke cross-wise and note the appearance of the fresh surfaces. Great care must, however, be taken in comparing one coke with another by this method, to break the pieces at approximately the same distance from the wall, since the size of the cells is apt to increase considerably from the wall to the center. In many cokes there is a characteristic difference in the two surfaces of a break. No matter where the piece is fractured, the surface on the wall side has almost a granular appearance with a steel-gray lustre and well defined cell openings. The opposite surface, *i.e.*, looking toward the center of the oven, has a characteristic graphitic lustre with the cell openings flatter and possibly not so sharply defined.

For an accurate comparison of the cell structure of different cokes, the writer prefers to make a longitudinal section with a thin emery wheel, such a section as is shown in Fig. 10. It must be mentioned that *breaking* a piece of coke longitudinally, so as to reveal the real cell structure, is a decidedly difficult matter. Almost always the break will be found to be made along the plane of a natural longitudinal fracture, and the exposed surfaces will be found to be covered with deposited carbon.

FIG. 10.—Natural surface and longitudinal section of by-product coke.

For grading the cell structure of cokes the writer employs a set of four standards shown in Fig. 11. These are all longitudinal sections cut from blocks of technically different coke. The sections are the same length and each is cut beginning 1½ in. from the wall end.

In addition to grading cokes according to the size of the cells, we may also classify them as regular or irregular in cell structure.

The standards would all be considered as regular in structure. This does not mean at all that the cells are of the same size, but their general arrangement gives an easily perceived impression of regularity. What is meant by irregular structure is illustrated by the sections shown in Fig. 12. This sort of coke has alternate patches of close and open texture and is frequently produced by the more highly oxygenated class of coking coals, as well as by mixtures of coals having decidedly different characteristics.

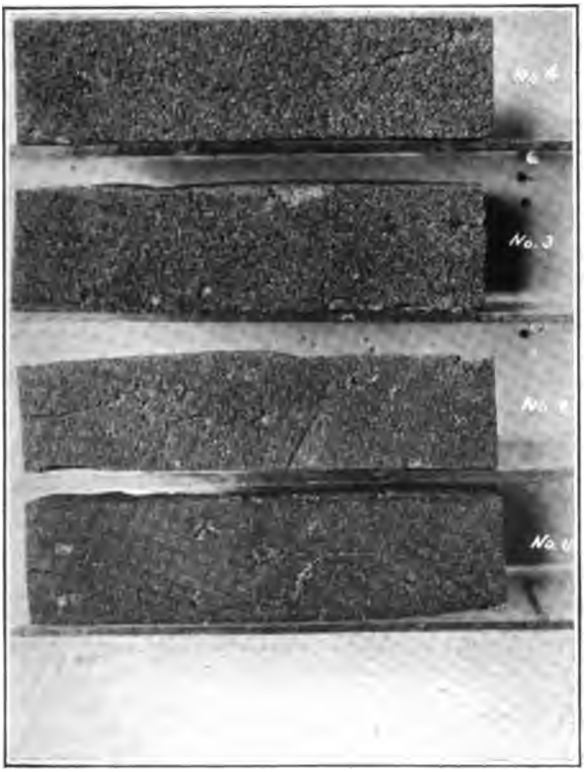

FIG. 11.—Standard sections of coke for grading cell structure.

In coking coals which, in the process of carbonization, produce an excess of binding material, this excess accumulates in the center of the oven, where it is eventually gasified with the production of a bulky, honeycombed mass, very appropriately called "sponge." Sometimes this sponge is found in loose detached masses scattered all over the coke as it lies on the wharf or bench after the quenching operation or, again, it may be found adhering very closely to the ends of the pieces of coke, and sometimes blending without any clear line of demarcation into the body of the coke itself. Although the amount of this sponge often appears to be very large, its actual percentage, by weight, is usually small. In one case, what appeared to be an unusually large amount of sponge was actually found to amount to 1.65 per cent. of the total coke. The coke-oven operator usually tries to eliminate it either by mixing with the high-volatile coal sufficient low-volatile coal to absorb the excess of binding material, or else by so proportioning the design of the oven and regulating the temperature that the conditions of sponge formation are eliminated.

Fig. 12.—Sections showing irregular cell structure.

Quite opposite in quality is that class of coals known as expanding coals, of which Pocahontas coal is typical. These coals, when coked in a by-product oven, tend to expand, wedging the mass of coke tightly against the walls and sometimes even distorting the brickwork. The expanding property appears most frequently in coals of less than 25 per cent. of volatile matter, in which the binding material is, apparently, just sufficient to saturate the mass of inert constituents, so that there is no tendency to shrinkage, but, on the contrary, a tendency to expansion due to the strong pressure of the escaping gases. Expanding coals cannot, however, be arbitrarily defined with respect to volatile matter. There are coals of less than 25 per cent of volatile matter that show no expansion, and there are expanding coals having more than this percentage. It is an important fact that the expanding property may be neutralized or counteracted by mixing a sufficient proportion of shrinking coal with the expanding coal. The proportion of shrinking coal required is generally small. The admixture of about 20 per cent of Pittsburgh coal is sufficient to counteract the expanding properties of Pocahontas coal.

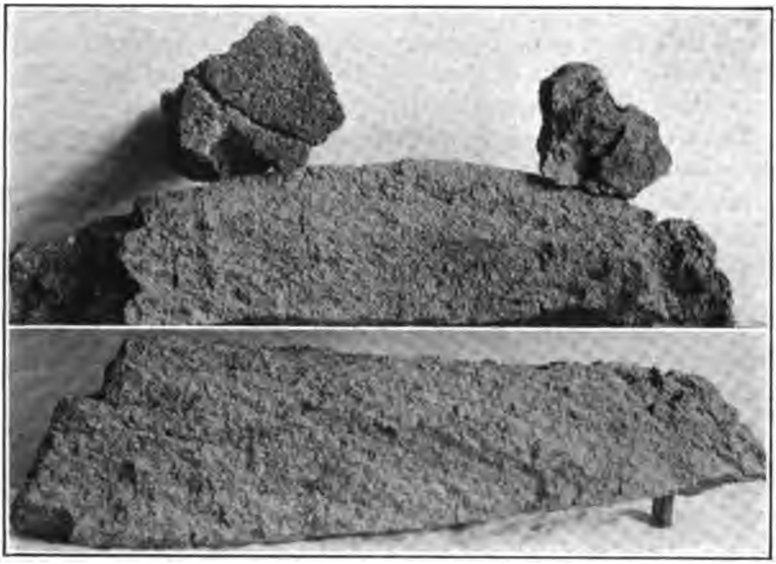

FIG. 13.—Beehive coke.

THE PROPERTIES AND CONSTITUENTS OF COKE: ITS USE AS A FUEL

Physical Characteristics.—The investigation of the physical characteristics of coke is hampered principally by the difficulties of securing properly representative samples, the material being, as we have seen, of exceedingly variable structure. The presence of slaty material more or less segregated also has a notably irregular effect on the results of any physical tests. Data taken from tests of only a few samples of any kind of coke should be used with the greatest caution.

Specific Gravity.—We naturally distinguish between the *apparent specific gravity* of a piece of coke including the cell spaces, and the *true specific gravity* of the coke substance proper. For methods of determining specific gravity, see page 217. The actual percentage of coke substance by volume

$$= \frac{\text{apparent specific gravity}}{\text{true specific gravity}}.$$

And the percentage of voids, or the *porosity*

$$= 1 - \frac{\text{apparent specific gravity}}{\text{true specific gravity}}.$$

The apparent specific gravity depends principally upon the amount of cell space in the coke, but it always must be remembered that there is no necessary relation between porosity and size of cells. A coke of close cell structure may, and frequently does, have a fairly high porosity.

The true specific gravity is possibly affected by differences in the molecular structure of the carbon itself; but this is often outweighed by variations in the percentages of mineral matter. Cokes of high-ash content always show relatively high true specific gravity.

The apparent specific gravity is decreased by rapid carbonization and increased by coking under pressure. Coke made from lump coal, tends to have a lower apparent specific gravity than that made from fine coal, as the following average figures show. The data were obtained on a West Virginia gas coal.[12]

TABLE XII

Character of carbonizing	Apparent specific gravity, fine coal (average)	Apparent specific gravity, lump coal (average)
Rapid heating, atmospheric pressure	0.73	0.71
Gradual heating, atmospheric pressure	0.76	0.71
Rapid heating, 20 lb. per square inch gas pressure	0.77	0.74
Gradual heating, 20 lb. per square inch gas pressure	0.81	0.76
Rapid heating, 20 lb. per square inch mechanical pressure	0.87	
Rapid heating, 50 lb. per square inch mechanical pressure	1.04	0.81

Table XIII gives data for various beehive cokes (Dewey[14]).

TABLE XIII

No.	Locality of coke works	Coke—specific gravity, porosity, etc., average						Coal—geological position and analyses					
		Moisture	True specific gravity	Apparent specific gravity	Per cent. of cells by volume	Volume of cells, c.c. in 100 grams	Weight per cubic foot, pounds	Geological formation	Water	V.M.	Fixed carbon	Ash	Sulphur
1	Broadford, Connellsville, Pa.	0.034	1.76	0.892	49.37	55.73	55.68	Pittsburgh Bed	1.105	29.885	57.754	9.895	1.339
2	Connellsville, Pa.	0.053	1.74	0.926	46.92	52.35	57.81	Pittsburgh Bed	....	31.36	59.62	8.23	0.784
3	Eagle, Kanawha, W. Va.	0.021	1.68	0.894	46.85	53.89	55.81	Middle measures (XIII).					
4	St. Clair, Kanawha, W. Va.	0.030	1.67	0.924	44.81	50.23	57.68	Middle measures (XIII).					
5	Quinnimont, New River	0.044	1.83	0.713	61.12	86.41	44.51	Lower measures (XII)	0.41	19.99	76.87	1.94	0.79
6	Sewell, New River, W. Va.	0.016	1.69	0.793	53.19	67.39	49.50	Lower measures (XII)	1.03	21.38	72.32	5.07	0.20
7	Stone Cliff, New River, W. Va.	0.074	1.74	0.838	51.79	62.30	52.31	Lower measures (XII)					
8	Fire Creek, New River, W. Va.	0.078	1.83	0.820	55.12	69.05	51.19	Lower measures (XII)	0.61	22.34	75.02	1.47	
9	Rockwood, Tenn.	0.192	1.69	0.935	44.81	48.55	58.37	Upper measures (XIV-XV).	1.75	26.62	60.11	11.52	1.49
10	El Moro, Col.	0.114	1.69	0.919	45.75	50.39	57.37	Laramie formation	1.14	29.97	56.32	12.57	
11	Crested Butte, Col.	0.073	1.59	0.907	42.96	47.59	56.62	Fox Hill group	0.72	23.44	71.91	3.93	
12	Leetonia, Ohio	0.047	1.49	0.770	47.59	62.23	48.09	Lower Kitt. seam	3.00	31.50	62.35	3.15	1.40
13	Wash. GasWks. D. C.	0.802	1.74	0.772	55.66	75.48	48.19						

TABLE XIII.—*Continued*
Information on coke samples

No.	Water	V.M.	F.C.	Ash	Sulphur	Phosphorus	Style of oven	Size	Charge pounds	Yield, per cent	Time of coking hours	Kind of furnace	Size of furnace feet	lbs. burden to 1 lb. coke
1	0.030	0.460	89.576	9.113	0.821	......	Beehive	11 ft. × 5 ft. 6 in. 12 ft. × 6 ft.	7,600	63	48 & 72	Iron blast	70×16	
2	0.075	0.412	88.655	10.055	0.805	......	Beehive	11 ft. × 5 ft. 6 in. 12 ft. × 6 ft.	7,600	63	48 & 72	Iron blast, etc.		
3	......	......	......	......	......	......	Beehive							
4	......	......	......	......	......	......	Beehive							
5	......	......	92.62	7.23	0.665	0.050	Beehive	9 ft. 6 in., 10 ft. 6 in., 11 ft. and 6 in. × 6 ft.	6,800; 8,500	65	48	Iron blast	60×16	2.2
6	......	......	93.00	6.73	0.027	......	Beehive	13 × 6 ft.	12,000	62	48 & 72	Iron blast	60×11	2.726
7	......	......	......	......	......	......	Beehive	11 ft. 6 in. × 6 ft.	9,000 to 10M	..	48 & 72			
8	0.216	0.390	95.894	3.500	0.563	0.0096	Beehive							
9	......	......	......	......	......	......	Beehive	11 ft., 12 ft., and 13 ft. × 6 ft.	100 bu.	..	48	Iron blast	65×14 65×16	2.29
10	......	......	......	18.00	0.50	......	Beehive	11 ft. 6 in. × 6 ft.	4.2 tons	60–65	48	Iron blast	65×15	2.0
11	......	......	......	8.70	0.48	......	Beehive	11 ft. 6 in. × 6 ft.	3.75 tons	70	48	Lead smelters, etc		
12	......	......	......	......	......	......	Beehive	12 ft. × 6 ft.	....	..	72	Iron blast	75×16	2.0
13	......	......	......	......	......	......	Retorts	....	....	..	....	Domestic		

NOTE.—Of the above No. 1 is the average of nine determinations, and the others of 12, for specific gravity, porosity, etc; of the coal analyses No. 1 is the average of two analyses and No. 5 of four- of the coke No. 2 and the sulphur in Nos. 10 and 11 are the average of two analyses.

For data on typical American by-product coke, see Table XIII.

The weight of by-product coke in bulk may be taken as averaging 30 lb. per cubic foot. The different commercial grades will run about as follows:

Blast furnace coke	30 lb.	Stove coke	35 lb
Foundry coke	25 lb.	Nut coke	37 lb
Egg coke	30 lb.	Breeze	42 lb

Crushing Strength.—This is very difficult of accurate determination, the slightest flaws and irregularities in the preparation of the test pieces, as well as the position and segregation of impurities, affecting the results enormously. The results are almost worthless for purposes of comparison unless a very large number of pieces are tested. Too much reliance often is placed on the practical value of this property. As pointed out in U. S. Geological Survey *Bulletin* No. **336,** calculation will show that even in a large blast furnace the coke does not have to withstand a crushing burden of over 50 lb. per square inch and a very poor coke will have sufficient strength to carry all the burden required. Fulton[16] takes the compressive strength as one-fourth the ultimate strength (apparently allowing a factor of safety of 4) and gives the following figures:

Coke	Method of manufacture	Compressive strength, pounds per cubic inch one-fourth ultimate strength
Connellsville	Beehive	301
Other Pennsylvania cokes	Beehive	170–316
Alabama	Beehive	192–409
Pocahontas, W. Va.	Beehive	236
Other West Virginia cokes	Beehive	200–381
Syracuse, N. Y.	By-product	340
Glassport, Pa.	By-product	804

According to Wagner,[15] the crushing strength is reduced by the presence of moisture. Comparative tests on 12 samples each of dry and wet coke, the latter containing 22.4 per cent of H_2O, showed a reduction of 14 per cent.

Resistance to Impact and Abrasion.—For practical purposes these qualities are much more important than crushing strength. The resistance to shock or impact is measured by the shatter test, for details of which see page 220. A very good coke may be dropped from a height of 10 ft. onto a hard surface without shattering. A moderately good coke is fractured, without completely breaking by a drop of 5 ft. The hard cokes emit a characteristic metallic ring when dropped, while many cokes of good grade, but tough rather than hard, give a duller sound, like blocks of hard wood. The poorer, friable cokes give a peculiar "sugary" sound.

Table XV gives some results of shatter tests made on typical American by-product cokes. Additional data for gas works and by-product cokes will be found in Table XVI.

The friability of coke depends upon the kind of coal, the amount and character of the mineral matter, and the rate and temperature of carbonization. Oxygenated or weathered coals, mineral impurities, slate, bone, etc., present in large particles, rapid heating and high temperatures, all tend to the formation of brittle coke. As remarked on page 89, the toughest cokes appear to be made from such coals or coal mixtures as produce neither an excess nor a deficiency of binding material during carbonization. The bad effects of large pieces of slate and bone, and of segregation of mineral impurities, may be overcome largely by fine pulverization and thorough mixing.

The resistance of coke to abrasion is not necessarily related to its friability, many comparatively soft cokes standing the shatter test very well. Unfortunately, we have little quantitative data as to this quality, which is to be regretted because such information would be of great practical value.

TABLE XV.—BLAST-FURNACE COKES FROM BY-PRODUCT OVENS

Mixture	Coal analysis				Coke analysis						Coke—Physical tests			
	V.M.	Ash	Sulphur	Per cent through ⅛ in.	H_2O	V.M.	Fix. Car.	Ash	Sulphur	Phosphorus	Shatter loss	Apparent sp. gr.	True sp. gr.	Porosity
Albama (washed)	29.3	7.38	1.39	....	9.52	1.15	89.95	8.90	1.17	0.052	28.0	1.128	1.937	41.82
Alabama (washed)	28.4	8.8	0.79	74.8	7.42	0.50	88.74	10.76	0.64	0.037	13.1	0.997	1.820	48.18
Colorado	33.1	12.63	0.68	....	4.00	1.86	81.86	16.28	0.57	.....	30.0	1.044	1.904	47.90
Pennsylvania	25.4	5.85	0.87	67.6	4.50	0.73	90.49	8.78	0.78	.....	16.0	0.883	1.967	55.20
Washington	31.5	11.31	0.50	45.0	2.85	1.16	84.91	13.93	0.47	.....	30.0	0.939	1.921	51.2
80 per cent West Virginia 20 per cent Illinois	21.0	8.12	0.87	84.0	3.61	2.07	86.41	11.52	0.73	0.0086	21.0	0.969	1.847	47.51
80 per cent West Virginia 20 per cent Pennsylvania	21.5	7.97	0.79	84.5	9.55	1.06	88.77	10.17	0.69	0.011	31.3	1.066	1.828	41.50
70 per cent West Virginia 30 per cent Kentucky	23.1	6.34	0.63	86.0	5.20	1.95	89.64	8.41	0.66					
40 per cent West Virginia 60 per cent Kentucky	29.3	5.48	0.52	....	2.56	1.34	89.72	8.94	0.49	0.005	26.0	0.863	1.821	52.41
40 per cent West Virginia 60 per cent Pennsylvania	28.9	6.73	0.77	85.0	4.48	1.47	88.31	10.21	0.67	0.008	22.5	0.900	1.911	52.91

TABLE XVI.—DATA ON CARBONIZATION OF COAL IN GAS RETORTS AND BY-PRODUCT OVENS[12]

Carbonizing vessel	Kind of coal	Size of coal, inches	Time carbonizing, hours	Shatter test, per cent on 2-in. screen	Specific gravity		Porosity,	Yield of coke, per cent	Per cent breese	Per cent volatile	Average temperature heating walls
					Apparent	Real					
20-ft. horizontal retort....	Elkhorn................	2 to ½	12	34	0.845	1.865	54.7	64	.....	1.1	1,700
	Elkhorn................	1 and under	8	36	0.885	1.850	52.1	66	.....	1.7	1,900
	Elkhorn................	1 and under	12	39	0.892	1.844	51.6	62	.....	1.4	1,910
	Elkhorn................	½ and under	12	49	0.882	1.860	52.6	64	5.0	1.7	1,700
	Elkhorn, 65 per cent Pocahontas, 35 per cent	....	12	56	0.863	1.836	53.0	69	.....	1.6	1,800
16-ft. horizontal retort....	Elkhorn................	2 to ½	8	24	0.910	1.866	51.2	64	7.0	1.3	1,900
	Elkhorn................	½ and under	8	42	0.994	1.874	47.0	....	5.1	2.1	1,900
	Elkhorn, 65 per cent Pocahontas, 35 per cent	....	8	43	0.872	1.890	54.0	66	7.5	1.3	1,900
	Elkhorn, 65 per cent Pocahontas, 35 per cent	....	24	52	0.953	1.950	51.0	67	.....	1.0	1,900
Ovens, 37 by 10 by 19 ft. and ¾ in..............	Elkhorn................	2 to ½	22	49	0.978	1.858	47.4	..	....	0.9	1,800*
	Elkhorn................	½ and under	22	46	0.929	1.808	48.6	..	.....	0.7	1,800*
	Elkhorn, 65 per cent Pocahontas, 35 per cent	....	22	58	0.940	1.884	50.0	..	.....	1.2	1,800*
	Elkhorn, 65 per cent	....	48	87	0.995	1.866	46.7	..	.....	1.8	1,400 to 1,600
	Pocahontas, 35 per cent	....	45	79	0.993	1.902	47.7	..	.....	1.8	
	Elkhorn, 60 per cent Pocahontas, 40 per cent	....	20	70	.....	.....	....	..	.....	....	1,900

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* This coke was obtained from coal enclosed in a steel box placed on a wide 2-in. plank, and then pushed just inside the oven on the coke discharging side. The 2-in. board was allowed to remain under the box while the coal was being coked. The top of the box was perforated for the escape of gas but allowed no pressure from the coal above.

Specific Heat.—Simmersbach[15] gives the following figures for the specific heat of Saar coke:

Temperature, degrees Centigrade	Specific Heat
100	0.1571
200	0.1765
300	0.1958
400	0.2152
500	0.2346
600	0.2540
700	0.2733
800	0.2927
900	0.3121
1,000	0.3314
1,100	0.3508
1,200	0.3702
1,300	0.3896
1,400	0.4089
1,500	0.4283
1,600	0.4477
1,700	0.4671
1,800	0.4864
1,900	0.5058
2,000	0.5252

The following are given for Ruhr coke:

Temperature, Degrees Centigrade	Specific Heat	Temperature, Degrees Centigrade	Specific Heat
750	0.377	950	0.394
840	0.390	1,050	0.400

The Volatile Matter of Coke.—The coking process is never in practice continued to the complete expulsion of all the volatile matter, and thus a sample, if reheated to a high temperature with careful exclusion of air, will always show a loss of weight. This is due partly to the presence of undecomposed compounds of carbon, hydrogen, and oxygen, and also to the presence of occluded gases which are by no means inconsiderable in amount.

Parry[20] has investigated the amount and nature of these occluded gases in different specimens of coke—20 grams of a hard, well carbonized coke, for example, gave, after2-hr. treatment in vacuo, 79.2 c.c. of gas of the following composition:

	Per Cent
CO_2	85.72
CO	5.59
H	5.68
N	0.00

A rather poorly coked specimen, which had been exposed to the air for some time, was treated in like manner and gave 91.7 c.c. of gas of the following composition:*

	Per Cent
CO_2	39.02
CO	7.69
H	53.32
CH_4	trace
N	0.00

Moisture.—The moisture present in coke is always of extraneous character, being derived from the operation of quenching or sometimes to exposure to rain. Dry coke may be considered practically non-hygroscopic. A. C. Fieldner, of the U. S. Bureau of Mines, has found that dry coke pulverized to 60-mesh may absorb as much as 0.2 to 0.4 per cent of moisture under conditions of high humidity.

Brought directly in contact with liquid water, as in the quenching operation, coke is, on account of its porosity, capable of absorbing large amounts of water. The following figures showing the average amounts of water absorbed by single pieces of coke (about 50 per cent porosity), completely immersed, will illustrate:

Time	Cold Coke Per Cent	Red-hot Coke Per Cent
30 sec	7.33	19.38
115 sec	11.56	19.12
1 hr	14.85	28.92

Naturally the larger pieces of coke absorb proportionately less water in quenching, and the moisture is always higher in the undersized coke obtained by screening the oven product.

Ash.—Of the common ash-forming constituents originally present in the coal, there is practically no volatilization during the process of carbonization. Exception may be made of iron and the alkali metals, small amounts of the former apparently going into the gas as ferrocarbonyl, while the latter, if present in comparatively high percentages, may be volatilized to such a

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* See also Thorner, *Stahl und Eisen*, **1886**, 71.

degree as to damage seriously the oven walls in course of time. However, for practical purposes—

$$\text{Ash in total coke} = \frac{\text{Ash in coal} \times 100}{\text{Per cent coke yield}}.$$

The ash is higher in coke screenings than in lump coke on account of the relative weakness of such portions as contain large particles of slaty material, which possess a marked natural cleavage. Large particles of mineral impurities in any form constitute an element of weakness.

On the other hand, a high percentage of ash is not necessarily indicative of a weak coke; finely distributed mineral matter often appears actually to strengthen the cell walls. Iron in excess of that combined with sulphur, appears to be present in combinations with carbon and silicon, and silicon itself has been shown to be present to a certain extent combined with carbon. Any such combinations must have the effect of strengthening and hardening the cell walls and their increased formation may account for the harder character of coke made at high temperatures. Some experiments in washing and coking coals of moderate ash content have shown that, where the original coal gave a strong coke, the washed coal gave a weaker coke, the difference being undoubtedly due to a considerable extent to the removal of some of the mineral matter. Small amounts of substances other than those usually determined have been occasionally noted, as shown in the following list:

SUBSTANCE	AUTHORITY
Selenium	J. F. Smith, *J. Soc. Chem. Ind.,* **1903**, 201.
Arsenic	Simmersbach.[15]
Antimony	Simmersbach.[15]
Lead	Simmersbach.[15]
Zinc	Simmersbach.[15]
Copper	G. Salet, *Compt. rend.,* **110**, 280.

Besides the constituents of coke indciated in the foregoing paragraphs, special attention should be given to phosphorus, nitrogen, and sulphur.

Phosphorus.—This element does not volatilize in the coking process, remaining in the coke probably in combination with calcium, so that the coke always has a higher percentage of phosphorus than the original coal.

Belden[21] gives the following ranges of phosphorus percentages in various American by-product cokes:

State	Per Cent of Phosphorus
Alabama	0.031–0.071
Illinois and Indiana	0.003–0.015
Maryland, Massachusetts, and New Jersey	0.004–0.012
Michigan, Minnesota, Wisconsin	0.010–0.012
New York	0.010–0.058
Ohio, West Virginia	0.012–0.035
Pennsylvania	0.011–0.022

Nitrogen.—The nitrogen present in coke is derived from the original nitrogen content of the coal, varying proportions of which are volatilized principally in the form of ammonia and hydrocyanic acid in the process of carbonization, while the remainder (usually much larger than the volatilized portion) remains in the coke, probably combined with the carbon.

Simmersbach[15] gives the following percentages of nitrogen in different coals:

Source	Per Cent of Nitrogen
Westphalia	0.84–1.77
Upper Silesia	up to 2.49
Austria	0.90–1.76
England	1.14–2.37
Scotland	1.93–2.11
North America	1.20–2.15
Bengal	2.12–2.48
Japan	2.85–3.62

The nature and behavior of the nitrogen compounds in coal and coke have been investigated exhaustively by M. G. Christie ("Studien uber das Verhalten der Steinkohlen—Stickstoffverbindungen bei hoherer Temperatur in bezug auf deren Konstitution," *Diss.*, Aachen, 1908). He found that the amount of nitrogen left in the coke increases with the geological age of the coal. This may be attributed largely to the relative amounts of oxygenated compounds in these coals, the younger coals with higher percentages of oxygen producing large amounts of steam and carbon dioxide, which favor the volatilization of the nitrogen. It is well known that the amount of volatile nitrogen produced in the form of ammonia from any coal is increased greatly by distillation with steam.

By slow distillation (88.5 hr. in an electric furnace at 860 to 880°C.) of peat and coals, Christie obtained the following:

RESULTS ON DRY AND ASH-FREE BASIS

	N in coal	Coke yield	N in coke	Per cent of total N in coke
Peat	1.14	31.74	0.86	24.02
English gas coal	1.65	64.68	1.09	42.63
Westphalian gas coal	1.82	68.57	1.16	43.60
Aachen fat coal	1.66	77.32	1.16	54.03
Anthracite	1.41	94.80	0.95	63.64

The percentage of nitrogen left in the coke is affected by various conditions of carbonization. Larger amounts are volatilized by slow than by rapid heating. A temperature of about 750°C. appears to be the most favorable for maximum volatilization. Above this temperature the percentage left in the coke increases.

Christie made a series of experiments to determine the proportion of the coke nitrogen capable of further volatilization under different conditions.

Duration of heating, hours	Temperature, degrees Centigrade	N in coke		Per cent of total N lost	Per cent of total N lost per hour
		Before heating	After heating		
12	850	1.58	1.61		
15	950	1.76	1.41	15	1
34	1,380	1.67	0.33	80	2
7	1,450	1.32	0.48	63	9
2½	1,800-1,900	1.67	0.21	87	35

Sulphur.—The volatilization of this element from the coal was long considered a most essential factor in the utility of coke for metallurgical purposes; but it is now recognized that this is of secondary importance in comparison with the qualities of the coke itself as a fuel. Under certain conditions the sulphur in the coke may actually amount to a higher percentage than that in the coal.

The principal proportion of the sulphur in the coal is usually present as pyrite (FeS_2). Varying percentages also exist in the form of organic compounds of unknown composition, which are the so-called "organic sulphur," the determination of which is attended with much uncertainty.* The presence of free sulphur has never been proved. Smaller amounts exist as sulphates, principally $CaSO_4$. Of these compounds, pyrite is decomposed in the coking process, with evolution of a part of its sulphur, leaving the remainder combined as FeS, Fe_2S_3 or possibly Fe_7S_8. Recent work by A. R. Powell and S. W. Parr[46] indicates that the amount of sulphide-sulphur thus retained is smaller than has hitherto been supposed. Secondly, reactions may occur with the formation of sulphur-carbon compounds. The organic sulphur is also volatilized in varying amounts, while that present as sulphate is reduced probably to sulphides.

The investigations of Powell and Parr have led them to the following conclusions which are important in this connection:

The sulphur of coal occurs in four characteristic forms, two of them organic and two inorganic.

(*a*) If the resinic organic type is shown to be organic sulphur by its lack of an ash, its presence in that portion of the organic material soluble in phenol indicates its association with that substance.

(*b*) The humus organic sulphur is shown to be organic by the very small amount of ash in the compounds in which it occurs. These compounds are shown to be closely related to humus substances by their chemical action.

(*c*) The pyritic or marcasitic sulphur is present as FeS_2 as indicated by the iron-sulphur ratio when the pyrites is oxidized and taken into solution.

(*d*) The sulphate sulphur is shown to be such, by the fact that it dissolves in dilute hydrochloric acid as sulphate without preliminary oxidation.

All four forms have therefore been definitely proved present, and only these forms exist in the coal, since the combined percentages account for all the sulphur. Free sulphur was not found in any of the samples of coal and is presumably absent except in

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* A. R. Powell, *J. Ind. & Eng. Chem.*, **12**, 887–90.

unusual cases where it might occur in small quantities as a decomposition product of pyrites.

. . . .

It seems probable from this investigation that, when the coal is coked, the sulphur forms of the coals change as follows:

(*a*) The sulphate sulphur is retained by the coke but in some form other than inorganic sulphate.

(*b*) The pyrite sulphur is partially volatilized and a portion is also left in the coke, probably as sulphide sulphur. All the pyrites is decomposed.

(*c*) Most of the resinic sulphur is left in the coke, but in a form different from that existing in the coal.

(*d*) The humus sulphur volatilizes partly but some is left in the coke in a changed form.

. . . .

During the coking process, secondary reactions between constituents of the coal and decomposed sulphur compounds affect the quantity of sulphur retained by the coke.

Whatever reactions actually occur in the coking process, it is certain that the percentage of sulphur remaining in the coke cannot be calculated from the percentage in the coal. Of 25 coals examined by A. S. McCreath[16] the percentage of sulphur expelled by coking in beehive ovens varies from 14.75 per cent to 57.92 per cent. The average loss of sulphur in the beehive oven for all coals in the country, as shown by tests made by the U. S. Geological Survey, is 43.27 per cent of that contained in the coal.[21] In by-product practice the fluctuations are also considerable. Averages computed by the writer for extended operation on four different plants show the following:

Coal	Per cent S in coal	Per cent S in coke	Coke yield	Per cent S eliminated
Illinois and West Virginia	0.87	0.74	84.0	28
Pennsylvania and West Virginia	0.79	0.69	84.5	26
West Virginia and Kentucky	0.57	0.48	70.5	40
Alabama	1.05	1.01	71.0	31

The case of the Alabama coal shows how a fair elimination of sulphur may yet leave almost as high a percentage of sulphur in the coke as was originally present in the coal. This is very likely apt to be the case when the coke yield is relatively low. The percentage of sulphur may even be higher than in the coal.

As a rule, the percentage of sulphur is considerably higher in coke screenings than in lump coke, although there are sometimes exceptions, especially if the coke is made from washed coal.

The Combustibility and Calorific Value of Coke.—C. Geiger ("Handbuch der Eisengiesserei") states that the ignition-point of coke is 700°C.

The calorific value of metallurgical coke is usually in the neighborhood of 7,200 cal. per kilogram (12,960 B.t.u. per pound). See Table XVII for data on American cokes. The following table ("Tables Annuelles," **1911,** 716) gives a comparison made by W. Inchley of the calorific value of various cokes, determined in the calorimeter and the values calculated by some usual formula.

TABLE XVII

Coke	Analysis			Calorific value (calories per kilogram)			
	C	H	O+N	K	K_1	K_2	K_3
Grand Combe Metallurgical	89.72	0.213	2.22	7,045	7,199	7,184	7,249
Commentry	93.19	0.446	2.64	7,703	7,838	7,841	7,606
Anzin	95.05	0.636	1.59	7,825	7,799	7,775	7,819
Nottingham Gas Works	91.40	1.02	0.15	7,543	7,785	7,787	7,657

K = Determined

K_1 = By formula of Dulong = $8{,}140\ C + 34{,}500\left(H - \frac{O+N-1}{8}\right)$

K_2 = By formula of Mahler = $8{,}140\ C + 34{,}500\ H - 3{,}000(O + N)$

K_3 = By formula of Tuckley = $8{,}000\ C + 33{,}830\ H$

H. Streit (*Diss.*, Univ. Zurich, 1906; *C.A.*, **1908,** 1,040) has made an elaborate study of the relation of the composition of coke to its heating value. He finds that, with a few exceptions, due to abnormal composition (*e.g.*, high sulphur), the calorific value of well burned gas coke can be calculated within about 1 per cent. by multiplying the percentage of combustible matter by 80. For well burned oven coke the factor is 79.5.

The Action of Carbon Dioxide on Coke.—This subject is of especial importance in its relation to the use of coke in the blast furnace; but, unfortunately, most investigations of it are vitiated by the fact that they have been conducted with samples pulverized to such an extent that the natural cell surfaces are destroyed, and the physical condition of the coke is so altered, that erroneous conclusions may easily be deduced from the results. As in all other investigations of coke, many experiments must be made in order to secure truly representative data. Different parts even of a single block of coke are attacked at different rates.

The reaction

$$CO_2 + C = 2CO$$

occurs, in the case of coke, to an appreciable extent at 500°C. and becomes rapid at 900°C.* Simmersbach† conducted 10 liters of CO_2 over 10 grams of coke (4 mm. size) for a period of 2 hours. In the first half-hour the loss was proportionately greater on account of the greater surface of attack offered by irregularities of the particles. For most cokes examined, the loss of weight at temperatures under 500°C. amounted to less than 0.5 per cent. At 500° and 600°C., the following losses of weight were observed:

TEMPERATURE C°	WESTPHALIA gram	SAAR gram	SAXONY gram	UPPER SILESIA gram	LOWER SILESIA gram
500	0.046	0.185	0.473	0.216	0.394
600	0.392	0.402	0.671	0.368	0.409

Coke as a Fuel.—Originally developed on account of the necessities of the iron industry, the manufacture of coke still finds in this its greatest source of demand. By far the greatest proportion of coke annually produced is used in the manufacture of pig iron, while large additional quantities are consumed in foundry practice. Other important uses for the material are in the smelting and refining of the non-ferrous metals, in the manufacture of water-gas and producer gas, in lime burning, and as a fuel for boiler and domestic purposes.

The oven coke of domestic origin consumed in the United States in 1915[35] was 40,341,223 net tons, of which 36,702,573 tons or 91 per cent was blast furnace coke and 1,664,548 tons or 4 per cent was foundry coke, principally used in cast iron manufacture, so that the iron industry in that year consumed

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* For studies on the equilibrium conditions of this reaction, see RHEAD and WHEELER, *J. Chem. Soc.*, **97**, 2,178; and **99**, 1,140.

† See also L. LÉVEQUE, *Bull. de Soc. Ind. Min.*, **1906**, 441.

TABLE XVIII.—TESTS OF AMERICAN COKES MADE BY THE UNITED STATES BUREAU OF MINES, A. C. FIELDNER, SUPERVISING CHEMIST

All figures are on dry basis

State	County	Proximate analysis					Ultimate analysis				B.t.u. per pound	Porosity, per cent
		Per cent V.M.	Per cent F.C.	Per cent ash	Per cent sulphur	Per cent phosphorus	Per cent hydrogen	Per cent carbon	Per cent nitrogen	Per cent oxygen		
Alabama	Jefferson	1.18	85.53	13.29	0.64	0.056	0.31	84.57	1.03	0.16	12,325	47
Alabama	Tuscaloosa	1.26	89.00	9.74	0.64	0.038	0.41	87.29	1.02	0.90	12,879	53
Georgia	....	0.97	92.75	6.28	0.76	0.007	0.59	91.43	0.90	0.04	13,433	50
Kentucky	Harlan	0.70	94.55	4.75	0.48	0.002	0.29	93.80	0.65	0.03	13,558	50
Ohio	Columbiana	0.98	88.34	10.68	1.00	0.010	0.16	87.01	1.04	0.11	12,746	39
New Mexico	Colfax	1.29	83.14	15.57	0.56	0.004	0.33	80.98	0.68	1.88	11,959	51
Pennsylvania	Bedford	1.19	82.42	16.39	1.90	0.006	0.43	80.55	1.02	....	11,869	48
Pennsylvania	Cambria	0.83	87.91	11.26	0.60	0.007	0.34	86.62	0.87	0.31	12,697	51
	Clearfield	0.88	90.67	8.45	1.39	0.018	0.20	88.59	0.63	0.74	12,953	42
	Elk	1.00	90.26	8.74	1.47	0.011	0.42	87.49	0.92	0.96	13,003	47
	Fayette	1.01	87.96	11.03	0.86	0.007	0.19	86.54	0.84	0.54	12,598	41
	Indiana	1.18	89.79	9.03	0.84	0.013	0.37	87.67	1.08	1.01	12,906	55
	Jefferson	1.05	85.06	13.89	0.85	0.018	0.21	84.16	0.76	0.13	12,206	44
	Lebanon	1.08	88.44	10.48	0.80	0.024	0.15	87.72	0.76	0.09	12,668	52
	Somerset	1.03	88.58	10.39	0.93	0.015	0.27	86.41	1.03	0.97	12,679	37
	Washington	1.40	87.75	10.85	0.90	0.007	0.36	85.64	0.94	1.31	12,596	47
	Westmoreland	0.75	88.38	10.87	0.96	0.013	0.25	86.29	0.96	0.67	12,625	47
Tennessee	Campbell	1.92	84.86	13.22	0.72	0.010	0.39	83.34	0.98	1.35	12,303	51
	Grundy	0.99	85.86	13.15	0.55	0.101	0.27	83.54	0.77	1.72	12,301	50
	Hamilton	1.86	82.32	15.82	0.81	0.025	0.26	81.98	0.83	0.30	11,961	43
	Morgan	1.04	84.57	14.39	1.77	0.008	0.08	81.96	0.96	0.84	12,150	47
	Roane	1.54	83.28	15.18	0.55	0.066	0.34	82.99	0.75	0.19	12,152	43
Utah	Carbon	0.73	87.97	11.30	1.20	0.045	0.38	84.31	0.90	1.91	12,600	49
West Virginia	Fayette	1.13	90.95	7.92	0.92	0.010	0.21	89.09	0.79	1.07	13,073	42
	Mercer	0.98	92.45	6.57	0.73	0.002	0.42	91.03	0.93	0.32	13,403	51
	McDowell	1.27	88.76	9.97	0.61	0.003	0.34	87.75	0.78	0.55	12,879	53
	Preston	0.76	84.94	14.30	0.75	0.011	0.18	83.82	1.05	....	12,184	48
	Randolph	0.71	82.57	16.72	1.17	0.043	0.18	80.80	0.78	0.35	11,788	36
Virginia	Wise	1.25	88.40	10.35	0.72	0.015	0.36	87.05	0.73	0.79	12.728	42

about 95 per cent of the total oven coke. To the remaining 1,974,102 tons may be added 1,662,552 tons of gas retort coke, which is almost exclusively used for domestic fuel and water gas manufacture.

As a metallurgical fuel coke is superior to its parent material, bituminous coal, in many important respects, of which we may enumerate the following:

1. Absence of volatile, smoke producing material.
2. Absence of fusing and coking properties.
3. Higher percentage of fixed carbon.
4. Lower ratio of sulphur to carbon.
5. Hardness.
6. Porosity.
7. Cleanliness.

The most important attribute of coke, to which several of the above mentioned qualities contribute, is its high calorific intensity. The heat produced by its combustion is concentrated within a relatively small area and this concentration is highly desirable in most thermal operations of metallurgy. In general, we may say that the most desirable qualities in a metallurgical coke are those that enhance its calorific intensity—such as absence of volatile material and fusing properties, high fixed carbon and porosity. The carbon itself should be in a condition to favor rapid combustion. As to what this condition is—molecular or otherwise—our conceptions are very poorly defined, but there can be no doubt that it plays an important part in determining the value of different cokes.

Opposed, possibly, to the qualities favoring high calorific intensity is the quality of hardness, which is, nevertheless, to a certain extent indispensable, because the coke is required to withstand abrasion by handling and by passing through the furnace in contact with its burden of ore or metal. Furthermore, the material must possess toughness or resistance to impact.

The Use of Coke in the Blast Furnace.—There is at present some disagreement among blast furnace men as to the exact function of the coke in the most efficient and economical reduction of iron ore. The majority probably still accept Gruner's theory of ideal working, *viz.*, as stated by Richards:* "All the carbon burnt in the furnace should first be oxidized at the tuyeres to CO and all reduction of oxides above the tuyeres should be

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* "Metallurgical and Chemical Calculations," p. 248.

caused by CO, which thus becomes CO_2." It is well known that the reduction of iron oxide by carbon monoxide is the most efficient from the standpoint of heat economy. Richards, however, has pointed out that the direct reduction of iron oxide by carbon is three times as efficient, from the standpoint of carbon required, as the indirect reduction, and says:

> "The ordinary furnace produces at the tuyeres, in order to get heat enough to melt down the charges, more CO gas than is needed to abstract all the oxygen from the charges; under these conditions it is uneconomical to oxidize any carbon at all above the tuyeres. The exceptional furnace, because of pure ores, small amount of slag, pure fuel, high temperature of blast, or dry blast, gives heat enough at the tuyeres to melt down the charges without producing enough CO gas to reduce all the charges; under these conditions, more or less reduction is effected by solid carbon and with the greatest economy in quantity of carbon required in the furnace."

The studies of some recent investigators, however, have shown that many furnaces are actually being operated with higher economy of coke than would be calculated from Gruner's theory. H. P. Howland has prepared an interesting set of tables on "The Performance of Twenty-six Typical Blast Furnaces," and a portion of his figures are shown in Table XIX. He calculates that all the furnaces burning less than 1,350 lb. of carbon at the tuyeres are not making enough CO to reduce all the Fe_2O_3, and hence some of the latter must be reduced directly by carbon. He concludes:

> "It seems clear, therefore, that, in low coke furnaces, one of the most important, if not the most important, function of the carbon burned at the tuyeres, is to produce heat to enable the carrying on of the direct reduction rather than to produce CO for indirect reduction.
>
> "On this basis, it becomes very essential that our carbon shall burn instantaneously to CO in order that the resulting heat may be localized where needed. This should not be a question of seconds but of a fraction of a second. If our carbon is of such a nature that this burning to CO is a comparatively long process, more of it will be required than of the quick-burning carbon in order to obtain the same concentration of heat at the desired point.
>
> "We would, therefore, say that the most desirable thing about a coke is that quality in the carbon which will allow of its being instantaneously burned to CO and thus result in the maximum concentration of heat where needed."

TABLE XIX

Furnace No.	Pound coke per ton iron	Tons iron per day	Carbon in coke. per cent	Kind of method of manufacture	Coke operation	Total charged	Gasified in furnace	Gasified at tuyeres	Per cent total carbon	Per cent gasified carbon
1	2,615	301	86.3	BH	Stonega	2,254	2,110	1,868	82.8	
2	2,551	272	84.4	BP	Solvay	2,153	2,049	1,751	81.4	86.6
3	2,472	482	86.1	BH	Conn.	2,128	1,996	1,728	81.2	86.8
4	2,247	450	87.1	BH	Conn.	1,957	1,846	1,605	82.0	87.0
5	2,198	499	86.9	BH	Conn.	1,908	1,810	1,494	78.7	82.6
6	2,123	541	88.3	BH	Conn.	1,875	1,764	1,498	79.8	84.9
7	2,115	360	84.3	BP	Solvay	1,782	1,683	1,427	80.1	84.8
8	1,996	490	86.3	BP	Koppers	1,722	1,611	1,298	75.4	80.6
9	1,936	376	85.7	BP	Solvay	1,659	1,557	1,305	78.8	83.7
10	1,905	393	88.7	BP	Solvay	1,690	1,575	1,252	74.1	79.5
11	1,901	517	85.5	BP	Koppers	1,625	1,524	1,280	78.8	84.1
12	1,863	504	86.6	BP	Koppers	1,614	1,513	1,230	76.2	81.3
13	1,780	426	84.9	BP	Koppers	1,511	1,414	1,124	74.4	79.5
14	1,742	503	84.6	BP	Koppers	1,474	1,382	1,133	76.9	82.0
15	1,716	542	87.1	BH	Benham	1,494	1,396	1,194	80.0	87.0
16	1,715	585	84.6	BP	Koppers	1,451	1,357	1,114	76.6	82.2
17	1,702	543	87.5	BP	Koppers	1,490	1,388	1,130	75.9	81.5
18	1,699	572	87.0	BP	Koppers	1,479	1,387	1,155	78.2	83.4
19	1,673	580	88.6	BH	Benham	1,482	1,384	1,182	79.9	85.0
20	1,658	590	88.3	BH	Benham	1,464	1,366	1,182	80.8	86.5
21	1,636	442	89.5	BP	Koppers	1,463	1,369	1,124	76.8	82.1
22	1,635	593	88.5	BH	Benham	1,447	1,349	1,124	77.7	83.4
23	1,624	592	87.3	BH	Benham	1,417	1,317	1,118	79.0	85.0
24	1,623	457	89.6	BP	Koppers	1,454	1,360	1,090	75.0	80.2
25	1,589	608	88.3	BH	Benham	1,403	1,307	1,100	78.5	84.2
26	1,584	466	89.2	BP	Koppers	1,413	1,324	1,057	74.8	79.9

NOTES.—BH = Beehive. BP = By-product. Conn. = Connellsville.

W. H. Blauvelt believes that the production of a high thermal head at the tuyeres is of the first importance, and the best coke is that which reaches the tuyeres in proper condition to produce the highest temperature, and in just sufficient quantity to do the amount of work required there under the conditions produced by this maximum temperature. The coke should be sufficiently strong to resist undue abrasion and crumbling by attrition with the stock and preferably of an open porous structure that will permit the most rapid combustion when it reaches the tuyeres. Many large users agree that the coke should never be overcoked beyond the point of producing a sufficiently strong structure, as overcoking quickly reduces the combustibility.* Some coke

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* It appears likely that overcoking promotes the formation of difficultly combustible graphitic carbon, and possibly such refractory compounds of carbon and silicon as carborundum (HEMPEL and LIEBIG, Z. *angew. Chem.*, **24**, 2,044; and ARSEM, *Trans. Am. Electrochem. Soc.*, **20**, 105).

might well be sacrificed by solution in the oxidizing gases in the upper part of the furnace, provided a sufficient quantity could be obtained at the tuyeres of a quality that would permit rapid combustion with the minimum amount of air, thereby producing the aforesaid maximum thermal head.

One of the prime requisites of blast furnace coke is uniformity of quality. This requirement of uniformity cannot be too strongly emphasized; and if it is fulfilled, satisfactory results may be obtained from any given coke chosen out of a wide range of origin. There is no one standard grade of coke to which all plants should conform so far as possible.

For each kind of coke, however, there is evidently some limiting size for efficient service; *i.e.*, just large, enough to offer such a minimum surface of attack for CO_2 that the loss on this account is negligible, and small enough so that complete combustion may be effected in a minimum of time at the tuyeres. Blauvelt calls attention to the desirability of having furnace coke of nearly uniform size, and states that many furnace managers are eliminating all coke below ¾ in. and above 4 in. or 4½ in. Much, however, depends upon what kind of coke is being used. One blast-furnace plant has successfully used coke of the following sizes over an extensive period of operation:[18]

On 2-in., Per Cent	On 1½-in., Per Cent	On 1-in., Per Cent	On ¼-in., Per Cent	Through ¼-in., Per Cent
75	17	6	1	1

This coke was produced from a mixture of 70 per cent high-volatile coal with 30 per cent Pocahontas. Blast-furnace coke made at another plant from a mixture of 80 per cent Pocahontas with 20 per cent Klondyke coals averages:

On 2½-in., Per Cent	On 1⅛-in., Per Cent	Through 1⅛-in.. Per Cent
40	40 to 44	16 to 20

The elements of size, hardness, and cell structure are undoubtedly closely interdependent in their relation to the value of coke. Hardness of body is usually (though possibly not necessarily) proportional to the resistance of the given coke to oxidation by CO_2 or oxygen. The harder grades of coke should be used in smaller sizes, and this is a compensation automatically provided to some extent by the operation of the by-product oven. Similarly, cokes of close cell structure are more resistant to oxidation, but this may be offset to a large extent by softness. The coke of more open-cell structure will probably require less rigid attention to sizing than the denser coke.

The prejudice against by-product coke that existed strongly up to less than 3 years ago has been altogether overthrown by the actual practical demonstration that such coke, when properly made and used, is actually superior in efficiency to beehive coke. Practically all blast furnaces of modern construction make better records of output and ratio of coke to iron with by-product coke than they formerly did with beehive coke. As a typical example, one furnace, with whose performance the writer has been closely acquainted, used 2,200 lb. of beehive coke per ton of pig iron as against 1,750 lb. of by-product coke. The difference is too great to be ascribed merely to the lower ash content of the latter. The uniformity in quality of the by-product coke plays a very important part and it is probable that there are qualities in the coke itself, as yet very imperfectly understood, that contribute to its efficiency.

The impurities in blast furnace coke that should receive special attention are moisture, ash, sulphur and phosphorus. The moisture content is of less importance than in the case of foundry coke; in fact, the general practice of wetting the stock in the upper part of the furnace would indicate that a considerable percentage of moisture could be tolerated with impunity. However, it is desirable that the moisture content should be as uniform as possible, and this condition is more readily attained with a low than a high average percentage of moisture.

Needless to say (other things being equal), the lower the percentage of ash, the better the coke. Ten per cent. of ash or less is desirable in the best blast-furnace coke, although many plants are obliged to operate with a considerably higher percentage than this. Like the ash, the sulphur in the coke requires the use of lime for its removal in the slag, and its presence in considerable amounts increases the expense and difficulties of operation. It is usually considered desirable to have less than 1 per cent sulphur.* In American blast-furnace cokes the amount of phosphorus is usually small and unimportant. This element,

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* Bolling (*Iron Age*, **81**, 760; **1908**, 1,262) concluded from the results of actual runs on high sulphur coke that the sulphur limit of coke for blast furnace use may run up to 2.0 per cent for basic iron without trouble if the slag is kept basic enough.

however, cannot be slagged off; but goes entirely into the iron, so that amounts of over 0.01 per cent are undesirable for making acid open-hearth or bessemer iron.

Coke in the Iron Foundry.—The conditions for efficient combustion of coke in foundry practice differ in several important respects from those obtained in the blast furnace. In the cupola, it is desirable that combustion should take place as rapidly as possible directly to CO_2, whereby the maximum temperature is obtained and the formation of CO should be reduced to a minimum. This is favored by using coke of relatively large size and rather dense cell structure or with heavy cell walls. Uniformity of size is desirable, Moldenke[29] recommends having the coke sized to about 4-in. pieces, though anything that remains on a fork with tines 3 in. apart is all right. The relations of size, cell surface, hardness and combustibility are as important to the foundry as to the blast furnace, although in a different way; but, unfortunately, very little practical experimental work has been done on the subject, and the selection of foundry coke is to a great extent a matter of individual caprice.

The conditions of shock and attrition to which foundry coke is subjected are even more severe than in the blast furnace, and the qualities of toughness and hardness are consequently all the more important. Good foundry coke should not show over 25 per cent loss in the shatter test.*

The impurities mentioned with relation to blast-furnace coke are even more undesirable in foundry coke. The percentage of moisture should be low and uniform. On account of the relatively short distance from the top of the charge to the zone of combustion, a high percentage of moisture in foundry coke would have a more decidedly detrimental effect than in blast-furnace coke. On the other hand, according to Moldenke, with very light cokes, the fact that they hold much water is an advantage, as it prevents them from catching fire and wasting too high above the melting zone. Ash detracts from the fuel value, although it may be of a certain benefit in assisting the formation of a good slag.[30] Sulphur should be less than 1 per cent High sulphur may lead to serious consequences. The effect of phosphorus naturally depends upon the grade of cast-iron that is being made. For the production of thin castings a high percentage of phosphorus may be actually beneficial.

* MOLDENKE, *Met. & Chem. Eng.*, **8**, 401.

The American Society for Testing Materials has adopted (1916) the following specification limits for the chemical composition of foundry coke:

	PERCENTAGE (IN THE DRIED SAMPLE)
Volatile matter	Not over 2.0
Fixed carbon	Not over 86.0
Ash	Not over 12.0
Sulphur	Not over 1.0

Domestic Coke.—For domestic consumption coke is largely sold in competition with anthracite, and for use in stoves designed for burning anthracite, and many producers and users believe that it should have qualities resembling the latter. On the other hand, coke has peculiar merits of its own, and, if properly used, is actually superior to anthracite. The main requirements of such a coke would be:[12]

> "That it should be clean and free from breeze and uniform in quality.
>
> "That it should be sufficiently tough to resist excessive breakage in handling.
>
> "That it should be of suitable size for the use to which it is to be put.
>
> "That the quantity of ash should be sufficiently low and its fusing temperature sufficiently high to prevent clinker troubles."

When properly made, coke ignites more readily than anthracite and produces a much smaller bulk of ash. In household furnaces, the most important point is to keep a large body of the coke burning slowly. The fire should not be too thin, otherwise the fuel will burn out in spots or produce clinkers. The draft should be maintained as low as possible.*

Coke for Miscellaneous Purposes.—The use of coke in connection with the smelting of the non-ferrous metals and for use in gas producers may be passed over without further discussion. As a fuel for lime burning a low sulphur content is the most important requisite. Coke is also employed to some extent for steam raising purposes.

With proper attention excellent results may be secured from the use of coke under small boilers. Nicol† cites the case of a Lancashire boiler with a weekely consumption of 27½ tons of bit-

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* JNO. H. WYMAN, *Prog. Age*, **1909**, 765, gives some interesting comparative data on the use of coke as domestic fuel.

† *Am. Gas. Inst. Abst.*, Jan. 1, **1917**.

uminous coal. During a 22 months' trial of coke, less than 23 tons per week were used at 15 to 20 per cent less cost per ton.

Use of Coke for Water-gas Manufacture.—An important application of coke is in the manufacture of water gas. The most important requirement is that the ash shall be as low as possible in amount and as high as possible in fusing-point. The fusing point of the ash should be over 2,400°F. for best results. A fairly large size is usually desired, but many plants are obtaining excellent results with egg coke. The inverse relation of size to hardness is important here as in the case of blast furnace coke.

Coke Breeze.—In by-product coke-oven operation we usually class as breeze that portion of the coke which passes through a ½-in. screen (square openings). The ½-in. screen may be considered as the dividing line between small-sized coke (pea and nut), which may readily be marketed for domestic purposes, and the breeze which cannot ordinarily be sold as domestic fuel. The attached table gives a few analyses of breeze made in by-product coke plants in different districts of the United States.

	Moisture, per cent	Volatile matter, per Cent	Fixed carbon, per cent	Ash, per cent	Sulphur, per cent
Lake District.......	12.0	3.5	84.5	12.0	0.70
Atlantic District....	12.0	4.0	82.0	14.0	0.80
Alabama District...	14.0	3.5	82.0	14.5	1.00

It will be seen that this material is really a fairly high-grade fuel. The calorific value of dry breeze is in the neighborhood of 12,500 B.t.u. per pound. The average sieve tests made on samples of breeze from one of the largest by-product coke plants in the Lake District gave the following results:

	Per cent
Through ½-in. and on ¼-in......................	23.79
Through ¼-in. and on ⅛-in......................	26.03
Through ⅛-in..................................	40.18

The material is difficult to burn by ordinary means, but has a high fuel value and recent improvements in combustion appliances have made its utilization entirely feasible and economical. Experience has shown that the use of forced draught is indispensable for proper combustion of this fuel. Several types of appliances, originally designed for the combustion of anthracite culm, have been found readily adaptable to the burning of coke breeze.

Figures 14 and 15 show a drawing and photographic view of the Coxe traveling grate, which is one type of stoker, primarily designed to handle anthracite culm and now successfully operated with coke breeze in several plants.*

The fuel supporting surface is made up of keys or grate tops which are small castings, approximately ¾ in. wide, 8 ft. long and 2 in. deep. The top surface is curved, and the front end of key matches the rear end of the next key. The keys are spaced about ¹⁄₁₆ in. apart to form the air openings and are carried on cast iron carrier bars. The ends of the carrier bars are fastened to the carrying chains, which are carried over sprockets at the front and rear ends of the stoker returning under the floor of the air compartments.

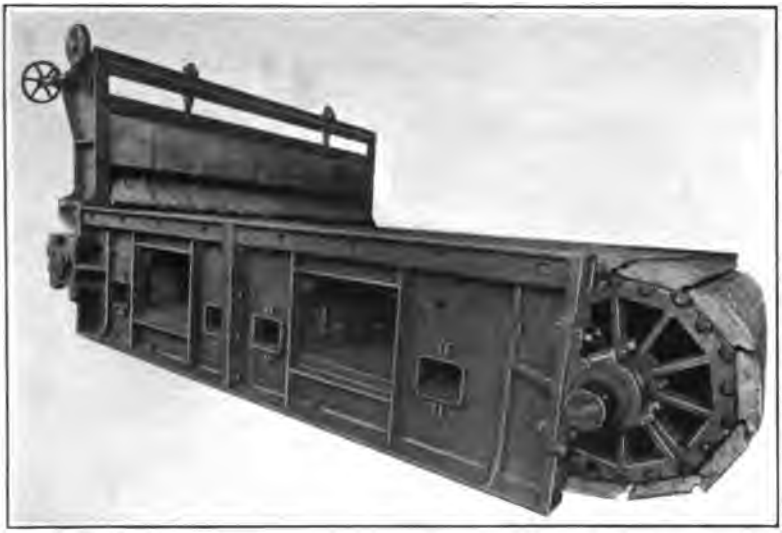

FIG. 14.—View of Coxe traveling grate for burning coke breeze.

On the front end of the stoker is a steel coal hopper, with a heavy iron gate lined with special firebrick tile on the sides toward the fire. The grate is operated by means of a hand wheel. At the bottom of the hopper, and supported between side frames, is a coal apron made of cast-iron sections and lined

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* The description of the Coxe type of stoker is taken from an article by W. A. HAMOR, in *Coal Age*, **11**, 780.

with firebrick. The upper ends of these apron sections may be lowered so that there is sufficient opening across the stoker to fire by hand when starting up.

The air for combustion is supplied by means of a fan or turbine at a static pressure of 2 to 2½ in. of water. The air passes through two tuyere boxes built on top of the floor and extending across the stoker. At the front and back side of each tuyere box are registers through which the draught may be admitted to the air compartments under the grates.

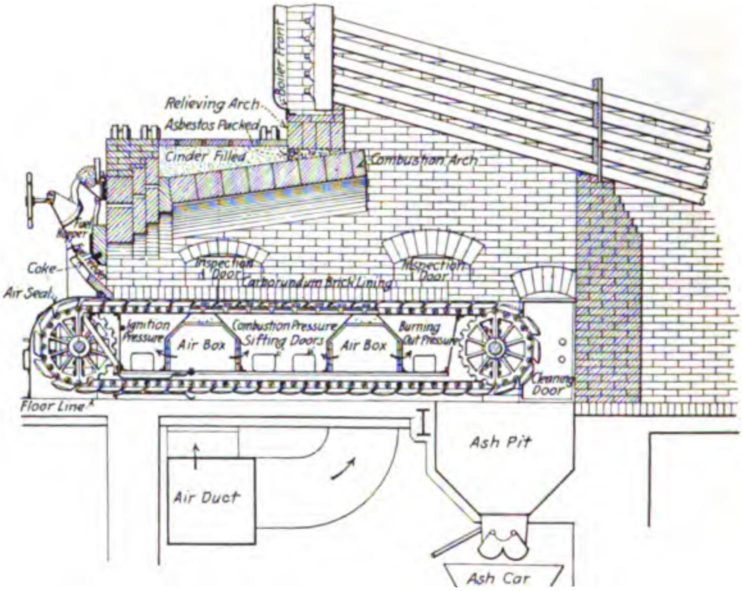

FIG. 15.—Sectional drawing of Coxe traveling grate.

The fuel is fed to a hopper extending across the front end of the stoker above the grate, the thickness of the fuel in the grate being regulated by an adjustable coal gate. Ignition takes place immediately and combustion is supported by forced draught under the grates. There are three or four air compartments each extending crosswise of the furnace; in each of which the air pressure may be independently regulated. It is possible to vary the rate of combustion over each air compartment as desired. At the rear end of the grate where it turns over the sprocket wheels, the ash is dropped off into the ashpit.

The three compartments may, for convenience, be called the ignition, combustion, and burning out compartments. Ignition takes place above the front compartment, and the bulk of the combustion over the second compartment, while the third compartment serves for burning out the remaining carbon at ordinary ratings. The function of these compartments is to enable the operator to vary the pressure under the grate in accordance with the thickness of fuel immediately above that section. The rear end compartment, or burning out compartment, is subdivided laterally into three separate compartments in each of which the air pressure may be separately controlled. Thus, if there is a tendency for the fuel to burn out on the sides, at the rear end, the side compartments may be closed and the air pressure retained in the center.

Under regular operating conditions in connection with a 500-hp. Rust boiler, one of these stokers developed from 150 to 200 per cent of boiler rating, with efficiencies ranging between 65 and 70 per cent. The ratio of water-heating surface to grate surface in the installation was 42 to 1. The breeze had the following analysis:

Moisture	8 to 12 per cent
Volatile matter	2 to 4 per cent
Fixed carbon	76 to 80 per cent
Ash	18 to 20 per cent
B.t.u.	11,500 to 12,000

The Parsons distributor has also been successfully used for burning coke breeze. C. J. Bacon* describes a series of tests with this distributor. It consists of a steam-driven injector blower which intermittently draws gas from the boiler furnace and projects it at high velocity against a small portion of the fuel, which is simultaneously delivered into the path of the gas by a reciprocating pusher. A test showed the efficiency and capacity of the distributor to be nearly the same with coke dust as with coal. Bacon also describes some work on the briquetting of coke dust, and this method of disposal offers many possibilities in the future.

Coke breeze also finds important application as a fuel in gas producers, although this method of utilization has not obtained such development in America as in Europe.

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* *Prog. Age*, **1912**, 378.

Ramsburg[28] gives the figures of a complete series of efficiency tests conducted by Karl Bunte on a set of Kerpeley-Mareschka producers, using a mixture of coke and breeze of the following size:*

	Per Cent.
0–11 mm	10.2
11–25 mm	43.3
Above 25 mm	46.5

The results of the tests showed a net efficiency of 81.9.

THE HISTORY OF COKE-MAKING

The primary incentive to making coke from coal is the demand for a cheap and efficient metallurgical fuel, and it is not until this is rendered imperative by the development of the iron and steel industry and the rapidly increasing scarcity of charcoal that we find the beginnings of regular coke manufacture. Coke was made in Germany as early as 1584[19]; but was not produced in large quantities until some years later. Following the practice of charcoal manufacture the coal was carbonized in earth-covered heaps, or meilers, a method which existed in England and America up to only a few decades ago. The process was considered essentially one of desulphurization—in fact, the early German word for coking was "Entschwefelung," the idea likely being derived from the color and odor of the volatile matter.

In England, Lord Dudley obtained a patent in 1619 for a process invented by his son, Dud Dudley, for making iron with the use of coke; but with the vicissitudes of civil war and other misfortunes that soon followed, the idea languished for nearly a century and was practically rediscovered by Abraham Darby in 1713. By 1735 the industry was well established. The material was originally called *coak*, a term of obscure origin, first used about 1686.[22]

Replacing the meilers and still following the methods of charcoal manufacture, beehive ovens were later used for coking and effected great economy in the yield of the product. Another very important industry producing coke, namely the manufacture of coal gas, was founded in England in 1792 by William Murdoch.† The coke from gas retorts was here a by-product—usually of a

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* See also Meyer, *J. Gasbel.*, **55**, 73.

† For an interesting account of the early history of gas manufacture, see Samuel Hughes, "A Treatise on Gas Works," London, **1871**.

very inferior character, and what was not actually employed for heating the retorts was sold for domestic fuel. For years the two industries underwent a parallel development; but, with the advent of the by-product oven, began to merge to a certain extent, and at the present time the by-product oven itself is becoming a powerful rival of the retort in the latter's own field.

It is curious, as pointed out by Lunge,[23] that by-products were recovered to a certain extent in the infancy of coke making—as early as 1768. Commercially, however, this was unimportant and it was not until 1856 that the first ovens for by-product recovery were constructed by Knab, near Paris, France. These ovens, as improved by Carvés, had horizontal heating flues in the side walls and thus were the originals of this important type of ovens of which the Semet-Solvay oven is the chief representative at present. Ovens of the vertical flue type were first constructed by Rexroth in Hermsdorf in 1858.[24] These were later modified and improved by Coppée in Belgium (about 1858).

One of the primary defects of the early by-product ovens was the enormous loss of heat in the waste flue gases. The flue temperatures were too low to produce a good grade of coke. A most important improvement to remedy this condition was made in 1882 by Hoffmann who applied the principle of the Siemens regenerator to the vertical flue type of oven. Hoffmann's first ovens, 10 in number, were built in Gottesberg in 1882 and this year may really be called the beginning of the modern by-product industry. Further improvements in this type of ovens were made by Otto in 1885. The recuperative system had already been applied to the opposite type (horizontal flue) by Semet and Solvay in 1884.

Comparatively few new forms of the horizontal flue oven have since been developed; but from the original vertical flue type has sprung an amazing number of modifications, of which the Otto-Hilgenstock, Collin, Still, and Koppers ovens are the most popular in present European practice. The design of oven invented by Heinrich Koppers of Essen, Ruhr, which has such a phenomenal popularity in America was first put into operation in 1903. The direct process for the recovery of ammonium sulphate, which is probably the most radical improvement that has occurred in by-product recovery, was introduced by Koppers in 1908. The recovery of benzol by scrubbing coke oven gas with an absorbing oil was first introduced by Brunck in 1885 and this method has been the basic principle of all subsequent benzol recovery systems.

In America the development of the coke-making followed the lines of growth of the European industry, passing first through the meiler and beehive stages, and finally arriving at by-product recovery. An interesting account of the history of the American coke industry up to the beginning of the by-product recovery period is given by Fulton[16] but can only be briefly summarized here. It is quite improbable that any coke was manufactured before the Revolution. It appears that coke was used in the Allegheny Furnace in Blair County, Pennsylvania, as early as 1811; but this was probably only a sporadic case. In 1835, the Franklin Institute offered a gold medal to "the person who shall manufacture in the United States the greatest quantity of iron from the ore using no other fuel than bituminous coal or coke, the quantity to be not less than 20 tons."

The first coke produced in the subsequently world famous Connellsville district was made in 1841 by two carpenters, Provence McCormick and James Campbell, and a stone mason, John Taylor. The partners were unsuccessful in attempting to market their product in Cincinnati and gave up their enterprise in disgust. The manufacture of beehive coke was not thoroughly established until about 1859; but thereafter it made rapid progress, not only in the Connellsville district, but also in other coal-mining sections.

The resources of coals suitable for coking in beehive ovens were proportionately much greater in America than in Europe and this fact, together with the comparatively smaller demand for the by-products of coking, retarded the introduction of the retort oven. The beehive oven received a great amount of attention and finally attained a degree of perfection in both construction and operation that has only recently reached its zenith and will probably never be surpassed on account of the rapid substitution of by-product ovens.

The development of the by-product oven industry in the United States was begun by the Solvay Process Company who in 1891 started the construction of 12 Semet-Solvay ovens in Syracuse, N. Y.[25] The design of this type of ovens had already been well established in Europe. An initial plant of Otto-Hoffmann ovens was built at Johnstown, Pa. in 1895 and began making coke in 1896. By the close of 1900[26] the number of completed ovens included 345 Semet-Solvay, 680 Otto-Hoffmann and 60 Newton Chambers, the latter[27] being a modified type of beehive oven adapted with apparatus for by-product recovery, that, like all similar hybrid designs, did not long survive. Of utmost importance in the development of the by-product oven was the use of silica brick which was first introduced in the Johnstown plant in 1899. This material was indispensable for the high temperatures, rapid coking, and high plant yields that were subsequently attained. Silica brick is not so much used in European practice, but Watson Smith* states that it was employed in a Simon-Carvés recuperative oven plant as long ago as 1833. An important improvement in by-product recovery was the system of gas separation introduced by F. Schniewind in 1899 in the plant of Otto-Hoffmann ovens at Evertt, Mass.

For a number of years, the progress of by-product coke making was slow, being retarded by imperfections of construction, difficulties of operation and finally by the deep rooted prejudice of blast furnace men against by-product coke. In 1908, however, the industry received a marked impetus as the result of the activities of the U. S. Steel Corporation, who after an exhaustive study of various European types of ovens and by-product apparatus, selected the Koppers design and built a 280-oven plant of this type in Joliet, Ill. This plant, which had the old indirect system of ammonia recovery, was successful beyond all expectations and was rapidly followed by the construction of large plants using the Koppers direct process, at Gary, Ind., Fairfield, Ala., and Duluth, Minn. The European war has caused an enormous increase in the construction of by-product ovens, and at present writing it would seem that at the close of another decade little should remain of beehive coke manufacture.

THE BEEHIVE OVEN

The name of the beehive oven appropriately describes its shape. The construction of typical ovens of this type is illustrated in Fig. 16. The ovens are built in single rows ("bank ovens") or in double rows, usually back to back, a bench being provided in front of each row at a convenient elevation, for loading the coke into railroad cars. The space above and between the ovens is filled with earth, broken stone or similar

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*J. Iron & Steel Inst., **1884**, 486.

material, and is leveled off to accommodate the larry track along which cars are operated to fill the ovens. A single larry track is used to fill a double row of ovens, the track being placed midway between the charging ports.

The oven is usually from 12 to 13 ft. in diameter, and 7 to 8 ft. high inside. The floor is constructed of two layers of firebrick, and the walls are also built of this material. The crown is usually built of silica brick. Underneath the firebrick flooring is a subfloor of red brick laid on edge in a sand bed on a firmly compacted foundation. This red brick subfloor serves not only as a support, but also to store heat to prevent the production of "black ends" in the coke.

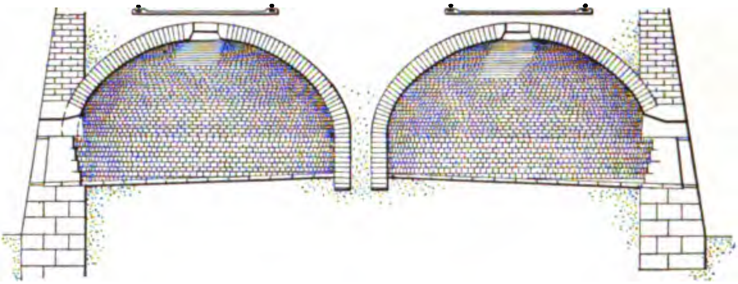

Fig. 16.—Beehive ovens.

The oven is provided with two openings, *viz.*, the charging hole or trunnel head at the top, and the door at the side by which the draft is regulated and through which the coke is watered and drawn. Iron door frames are usually provided and especial care must be taken in the design and construction of the jambs and door arch, since these are the parts that are subjected to the greatest wear.

"On starting a block of ovens a fire of wood and coal is built and the door bricked up and daubed with loam, leaving a bottom draft for quick burning of the coal. After the ovens are heated for a time, depending upon the amount of heat absorbed by the firebrick, the door of each oven is torn down and the oven thoroughly cleaned. The door is then bricked up to a point where the leveler can conveniently handle his scraper and a small charge of coal is put in through the "trunnel head." After one or two burnings with small charges the oven is in shape for continuous work."[21]

Beehive coke is graded according to the coking period employed to produce it, as 48-hr. coke, 72-hr. coke, etc. The 48-hr. charge is usually about 23 in. deep in a 12-ft. oven, equivalent to about 5 tons, while the 72-hr. charge is about 6 tons, 26½ in. deep. The coal is usually crushed previous to charging. The charge is leveled either by hand or by a mechanical scraper, and the door is bricked up to 2 or 3 in. of the top. The heat of the previous charge starts a distillation of the coal and soon the volatile matter ignites in the upper part of the oven. The regulation of the combustion of this volatile matter is the all-important matter in the coking process.

To obtain the maximum efficiency of operation and output, the admission of air should be regulated so as to burn the volatile products without consuming any of the fixed carbon of the coke. As carbonization proceeds, the evolution of volatile matter decreases and the air opening must be gradually closed up.

When coking is complete the brickwork in the door is torn out and the coke is sprayed with water until it may be drawn without risk of ignition.

The drawing is often done by hand although the scarcity of manual labor has gradually forced the introduction of coke-drawing machines. The same cause has also brought about the introduction of a modified type of beehive oven adapted to the rapid discharge of the coke by pushing it out with a ram as is done in by-product ovens. The so-called longitudinal oven[21] consists of a long, narrow, rectangular chamber, generally somewhat larger at the discharging end, with a flat tile bottom, a sloping barrel roof approaching from both ends, a trunnel head in the center of the roof, and doors the whole width of the chamber at either end. These ovens, placed side by side, form a block and are charged, as are beehive ovens, from a larry running on a track on top of the ovens. The oven is supplied with air from both ends, after the method of the beehive oven, and the coke, after being watered inside of the oven, is pushed out by means of a special pusher on to a traveling conveyor. This conveyor transfers the coke to cars, screening being more or less fully accomplished during the passage of the coke along the conveyor.

Great advances have been made in recent years in the utilization of waste heat from beehive ovens. Some of the most complete information that has appeared in literature on this subject is given by Arthur D. Pratt.*

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* *Met. & Chem. Eng.*, **1917**, 27.

From the nature of the beehive-oven coking process, the quantity of gas produced is very large, but extremely variable in quality during the different periods of operation. For estimating purposes, the gas weight available may be taken as from 6 to 7 lb. per pound of coal coked per hour. The temperature of the gases leaving the individual ovens probably average 2,000 to 2,200°F. With suitable arrangement for heat installation and careful baffling in the boiler, modern installations have been successful in using a large percentage of the heat with very low exit temperature (460 to 480°F.). For the exit of gases tested on an installation of Babcock and Wilcox boilers show that 1 hp. was developed from the waste gases from less than 15 lb. of coal coked per hour.

TYPES OF BY-PRODUCT COKE OVENS

Lack of space forbids a description of all the various designs of ovens and by-product recovery apparatus now being used in European practice, and the following sections of this Chapter will be devoted to the comparatively few types that have gained a successful footing in America. For an account of the more important European oven designs the reader is referred particularly to articles by Berthelot,[31] Christopher,[32] Coppee,[33] and Meissner.[36]

According to the utilization of the waste gases from the heating flues, the various types of ovens may be classified as follows:

(*A*) The waste heat is not used for preheating the air or gas that go to heating the ovens.

(*B*) The waste heat is used in recuperators for preheating the air and gas.

(*C*) The waste heat is used in regenerators for preheating the air and gas.

Plants of type-A are of simple construction; but require practically all of the gas produced in the coking process for heating the ovens. The waste heat may be used for steam-raising purposes; but in any event the total heat economy of the system is much less than in types B and C, and modern American practice favors these two latter, with a marked preference for type C.

In present practice, most by-product coke ovens are heated with their own gas and only the air is preheated. It is neither desirable nor economical to preheat such gas, one of the principal practical difficulties being the decomposition of the hydrocarbons and deposition of carbon that would result. On the other hand, ovens designed to be heated with gas of relatively low calorific value, such as producer gas or blast furnace gas, are being installed in increasing number, and such ovens necessarily have arrangements to preheat both gas and air.

The utilization of the hot products of combustion for preheating the air involves the application of either the recuperative (Type B), or the regenerative principle (Type C). In a recuperator the cold air is heated by causing it to pass through flues or chambers the walls of which are kept hot, by continuous circulation of the hot gases in a direction parallel and opposite to the flow of the air. The direction of flow of both gas and air is always constant.

In the regenerative system there must be at least two reservoirs of heat and the direction of flow of gas and air must be periodically reversed. The reservoirs are chambers filled with refractory checkerwork. The hot gases are circulated through one chamber during any given period and give up their heat to the checkerwork while simultaneously the air is passing through and abstracting the heat from the opposite chamber, that has been heated during the previous period.

It is a well recognized fact that, with the high temperatures prevailing in coke-oven practice, greater economy of heat is obtainable through the use of the regenerative system,* and so, notwithstanding the greater simplicity of operation of the recuperator, practically all modern coke oven installations are built with regenerators in one form or another.

We may now re-classify the various designs of ovens according to the arrangement of their heating flues. As has been already noted in the historical paragraphs at the beginning of this section, there are two principal root-forms of by-product ovens namely:

I. Horizontal flue ovens.
II. Vertical flue ovens.

Class I comprises such designs as the Simon Carvés, Rothberg, and Semet-Solvay, while in Class II we find a far more numerous variety, including the Otto-Hoffmann, Otto-Hilgenstock, Coppée, Koppers, Still, Collin, Bauer, and many others.

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* See Damour, "Industrial Furnaces," translated by Quenan, New York, **1906**, for a comparison of the two systems applied to furnaces in general.

The design of the horizontal flue type of oven is in some respects better adapted to the use of recuperators than of regenerators, and the great majority of oven installations of this type used the recuperative principle. The Semet-Solvay Company has, however, recently built a number of its ovens with regenerators, as will be described later. The ovens of Class II that utilize their products of combustion for preheating the air are practically all equipped with regenerators.

THE HORIZONTAL FLUE OVEN

Of the ovens mentioned under Class I, the Semet-Solvay is the only one that has found extensive application in America. The Simon Carvés oven although much used in Europe has not been built in America, and there is only a single installation of Rothberg[1] ovens now in operation. The Semet-Solvay oven will, therefore, be described as representative of this type.

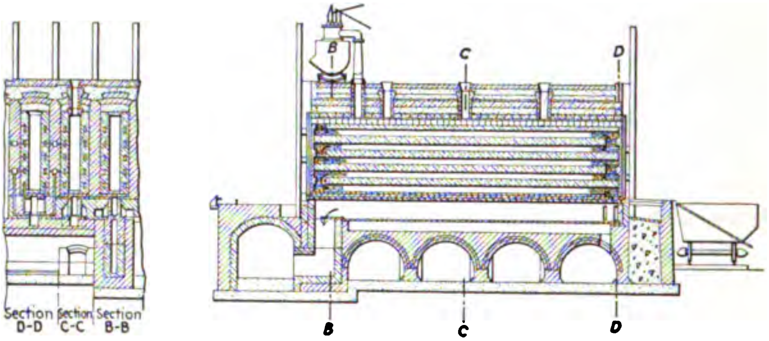

FIG. 17.—Sectional drawings of Semet-Solvay recuperative oven.

Figure 17 shows longitudinal and transverse sections through a Semet-Solvay recuperative oven with its heating flues. These ovens are, in technical parlance, classed according to the number of flues in a single oven wall, as "3-high," "4-high," etc. Seven-high ovens have been built but the size generally used is the 6-high.

Each oven has its own system of heating flues, separated from those of the adjoining oven by a partition wall about 18 in. thick, which serves to support the weight of the brickwork above the oven. The air for combustion passes through the recuperator in, which it is preheated by the products of combustion flowing in an opposite direction. From the recuperator, the preheated air is distributed into risers located at the ends of each set of flues. From each riser the air passes into the flues through openings the width of which is controlled by sliding bricks.

The fuel gas mains are located near the top of the battery of ovens, one main being provided for each side of the battery. Pipes pass down from the mains opposite the flue walls, and from these pipes small burner pipes convey the gas into flues. The flues are operated in series in the following manner:

Gas and air are admitted into one end of the top flue and combustion takes place along this flue, the products passing down into the next. Additional gas and air are introduced into the next flue at (*b*), into the third flue at (*c*), and so on down until the last flue is reached. Thus, the flues receive increasing quantities of gas and air, and the area of each flue must be made enough larger than the flue just above. Part of the products of combustion pass through the bottom flue and part through a sole flue located directly under the bottom of the oven, the proportion of distribution being regulated by sliding bricks.

The Semet-Solvay Company has tried the plan of operating the flues in parallel, but abandoned it in favor of operation in series. The dilution of the gas and air in each flue by the products of combustion from the flue above undoubtedly aids in the propagation of a long flame and facilitates uniform heating.

W. H. Blauvelt of the Semet-Solvay Company has published[39] the following description of a regenerative oven which he illustrates by the diagram shown in Fig. 18. This diagram shows the operation of the heating system during one half of the reversing cycle. Each oven is provided with two individual regenerators, one at each end, with chimney flues between each pair of regenerators, as shown.

During one reversal period, the gases flow upward through the flues, the products of combustion eventually passing down into the regenerators on one side. During the next period, the air for combustion is drawn through the regenerator just heated and the gases burn downwards, eventually passing into opposite regenerators.

The air is usually blown in by a fan located beyond the reversing damper and is distributed under the block through a single chimney flue. It enters at the bottom of the regenerator, rises and passes through the flue system, meeting the gas at the several burners in the combustion flues. On reversal, the air enters the other regenerator, rises through the air flue, shown in dotted lines, and descends through the horizontal combustion flues, meeting the gas as before. The products of combustion pass out through the other regenerator to the reversing damper and stack in the usual manner.

When the air is traveling downward through the system, it flows through the first flue until it reaches the first gas burner. The stream of gas is deflected downward by the air current and burns in the air as it travels through the flue. At the end of the second flue, the air meets another stream of gas, which also is deflected downward and heats the third flue and so on, until the gas from the last burner consumes the last of the oxygen.

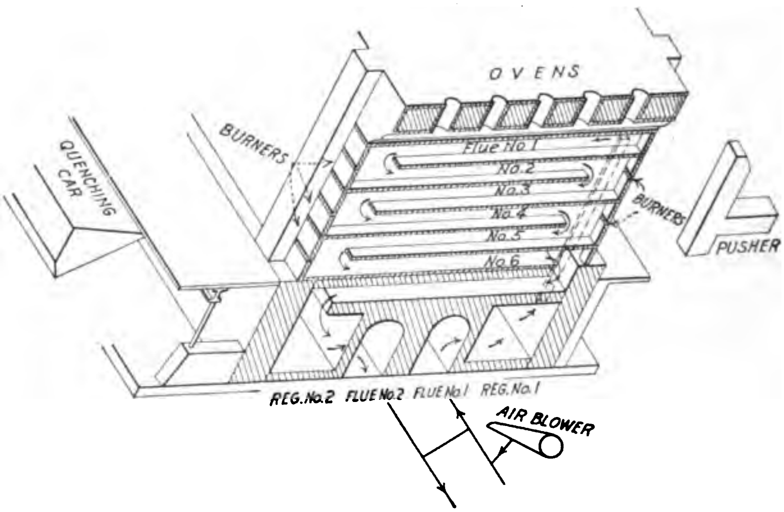

FIG. 18.—Diagram showing heating system of the Semet-Solvay regenerative oven.

When the air current is traveling upward, the streams of gas are deflected upward, so that the entire combustion system is reversed at the usual half-hour periods by the manipulation of only one reversing damper for the entire block of ovens. A proper adjustment of the relative amount of gas delivered by each of the burner pipes maintains just the right relation between the heats in the different parts of the system, with the minimum attention. This method insures an even distribution of heat throughout the whole heating system.

The flues may be inspected through peep holes at the ends of each, and the proportions of gas and air are adjusted by valves and sliding brick. It is the usual practice to have a gas meter of the Venturi type in connection with each fuel gas main, and to adjust the gas so that consumption takes place at as uniform a rate as possible. Fixed orifices are also placed in the individual burner pipes, so that the amount of hand regulation is reduced to a minimum. In a journal report* there is a description of a Semet-Solvay regenerative oven built at Ashland, Ky. This oven is illustrated by the diagram reproduced in Fig. 19. The ovens are described as 36 ft. long, 12 ft. high and 21 in. wide, with a 2 in. taper, and having an average capacity of 16 tons of coal per charge. Other Semet-Solvay Regenerator Oven plants are illustrated in the photographs (Figs. 20, 21, and 22) of Semet-Solvay ovens at the Ford Motor Co., Detroit; The Steel and Tube Company of America, Indiana Harbor; and the Sloss Sheffield Steel and Iron Co., North Birmingham, Ala. In the last named plant, there are 120 "six-high" ovens. These are 36 ft. long, 17.5 to 19.5 in. wide, and have a capacity of approximately 16 tons of coal per charge.

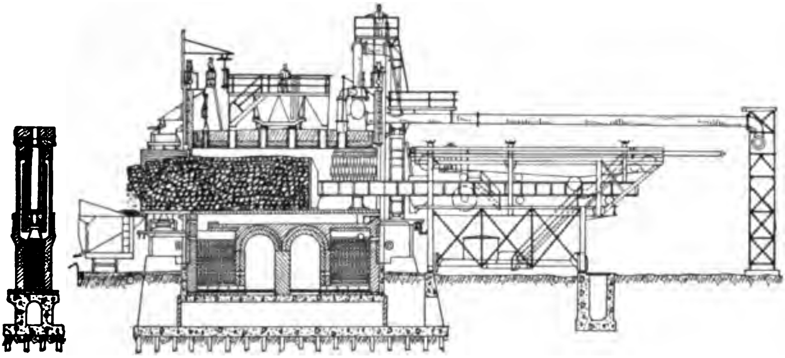

FIG. 19.—Semet-Solvay standard regenerator cokeoven.

The advantages claimed for the horizontal flue type of ovens are:

1. The temperature of the top flue may be independently regulated so as to maintain a low heat in the top of the oven.
2. The flues are located so that inspection and regulation is very convenient.
3. The number of gas burners and, consequently, the amount of gas regulation is reduced to a minimum.

* *Iron & Coal Trade Rev.*, July 13, 1916.

4. The central partition wall makes it possible to repair any oven and still maintain the adjacent ovens in operation.

Fig. 20.—Semet-Solvay plant built for Ford Motor Company, Detroit, Mich., showing pusher side of oven with pusher in position.

Fig. 21.—Semet-Solvay ovens built for Steel & Tube Company of America, Indiana Harbor, Ind., showing general arrangement of ovens and coal-handling equipment.

5. The central partition wall acts as a heat reservoir and steadies fluctuations of temperature.

6. The reversing mechanism, in the case of the regenerative oven, is of extremely simple nature, merely operating two dampers at the chimney base.

Notwithstanding these claims, the great majority of coke oven designers prefer the vertical flue type, as is evidenced, among other things, by the large number of patents relating to this type. In 1914, Berthelot[31] estimated that only 5 per cent of the world's by-product coke ovens were of the horizontal flue type.* The objections urged against the Semet-Solvay oven are of the following nature.

FIG. 22.—Semet-Solvay plant built for Sloss-Sheffield Steel & Iron Company, North Birmingham, Ala., showing discharge side of ovens with quenching-car and coke-belt.

1. A horizontal flue structure is fundamentally weak from a mechanical standpoint. It requires the use of heavy partition walls for supports and such walls add materially to the size and expense of construction and maintenance of a battery designed for a given output of coal.

2. The brickwork forming the horizontal flues cannot be made so permanently tight as the vertical flues, consequently there is apt

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* It is estimated (*Gas World*, April 1, **1916**, Coking Section, p. 18) that there were in 1916, 72 plants having a total of 4,749 Semet-Solvay ovens in operation in various parts of the world, and 12 plants having 553 ovens under construction.

to be serious leakage of gas from the oven into the flues of the former type of oven, or *vice versa.* Consideration of the principles of any vertical flue structure will show that its members can be designed to interlock and form a practically gastight joint, which is not easy to obtain in the case of a horizontal flue.

3. The temperatures of a horizontal flue oven are apt to be irregular and cannot be so well controlled as in a properly designed vertical flue oven. Any irregularity of temperature in a single horizontal flue, which, in the case of a six-high oven affects about 17 per cent of the heating surface, is of much greater consequence than in a single vertical flue which affects only 3 per cent of the heating surface. Furthermore, most by-product ovens must be designed with a taper to facilitate pushing the coke, *i.e.*, they are from 1 to 4 in. wider on the discharge end. This requires that the flue temperatures be gradually increased toward the discharge end so that all of the charge will be uniformly carbonized. The very nature of the horizontal flue oven renders this difficult to accomplish, whereas the vertical flue oven is well adapted to such regulation.

THE VERTICAL FLUE OVEN

The differences in detail, upon which the numerous patents relating to vertical-flue ovens are based have mostly to do with the arrangement of the heating flues with respect to reversal of fuel gas, air, and products of combustion. The evolution of the Otto-Hoffmann oven is an interesting example of how the numerous possibilities of design have been utilized.

Meissner[36] classifies the methods devised by the Otto interests to secure economical and uniform combustion as follows:

1. Three tier gas burner plan. In this system the gas is introduced from the main into the combustion chamber by three gas pipes located in a tier at each end of the combustion chamber. There are usually 32 vertical flues per oven, 16 in each half. One burner supplies gas for the first four of these vertical flues, the second supplies gas for the second six, and the third burner supplies gas for the rest of the vertical flues in this half of the oven. The combustion chamber is arranged in three sections, each communicating with its own burner.

2. One gas burner for each two vertical flues. In this method the gas is introduced into the combustion chamber in a 32-flue oven, from 16 burner pipes entering the combustion chamber

from below the ovens. In this way, one gas entry is provided for each two flues.

The heating operation is conducted as follows: Supposing the gas burners are numbered from 1 to 16. During ½ hr., gas enters the combustion chamber from burners 1 to 4 and 9 to 12, and the products of combustion travel through the vertical flues supplied from burners 5 to 8 and 13 to 16, respectively. The next half hour this process is reversed, and so on.

In this method of travel of the off-heat gases appear to be under better control than in the former method of heating, on account of not having to travel so far. In other words, the off-heat is withdrawn from each quarter of the oven instead of from each half.

3. One gas burner for each vertical flue. This is the latest method and has not been exhaustively tried out as yet. Theoretically the results ought to be better than the other methods described.

The products of combustion are withdrawn similarly to the scheme described under head of "One gas burner for each two vertical flues."

4. American system of end burner and under burners. After using various methods of heating, none of them so far as known, following any exact German methods, but always comprising some modification, the American representatives of the Otto type of ovens have practically settled on a system of heating, employing one end burner and two auxiliary or under burners for each half of the oven. That is, the gas enters the combustion chamber through a burner located at the end of the oven wall, and any further gas supply which may, in the judgment of the heater, be required, is furnished by the two under burners, which deliver gas into the combustion chamber from the alley ways below.

An essential point of difference in the American system is the fact that only one downtake for products of combustion to the regenerators for each three ovens is provided, and *vice versa* one air intake. In Germany, special stress is laid on the necessity of having an individual downtake for each oven.

The Otto system of regenerators are of the long type, two being provided running the entire length of the battery.

In order of development in Germany and America, the end burner oven was the first to be adopted. This original oven is not exactly covered in Meissner's classification, there being only a single burner introducing the gas from the main into the combustion chamber at each end of the flue wall. The original Otto-Hoffmann oven, as built at Johnstown and Glassport, Pennsylvania; Everett, Massachusetts, and several other places in America, is shown in Fig. 23. The oven chambers are 33 ft. long, 18 to 20 in. wide, and 6 ft. high, the oven having a capacity of about 6 tons of coal.[40] The ovens are separated by a division wall containing vertical flues through which the heat is supplied. The foundations consist of masonry arches running lengthwise of the battery, the two outer arches forming the regenerative chambers. Through these regenerators the outgoing hot gases and the incoming air for combustion pass alternately. The regenerators are provided with reversing valves at the ends of the oven battery in connection with the necessary chimney stacks. The gas is admitted alternately by two burners, one at each end of the oven, to the space beneath the division wall flues. The air for combustion rises from the regenerator below to the space beneath the oven floor and passes to the combustion chamber beneath the flues. The passage of the hot gases is up the vertical flues in one-half the division wall, along the horizontal flue at the top, and down the flues at the other half of the division wall to the regenerator below. This type of oven was developed in Germany and America by allied interests (Dr. C. Otto and Company of Germany and the United Otto Company of America) along parallel lines, the most radical innovation being introduced by G. Hilgenstock of the German

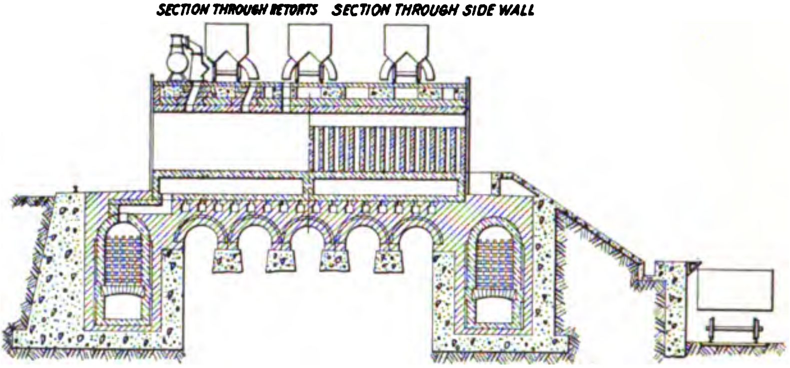

Fig. 23.—The Otto-Hoffman coke oven.

company, who designed the so-called "under-burner" oven. The original under-burner oven is shown in Fig. 24. The regenerators are omitted, the waste heat of the flue gases being employed for steam raising. The fuel gas is carried by a separate main under each oven; from this main burner pipes rise to the combustion chambers underneath the vertical flues. One of the most essential features is the arrangement permitting inspection of the burners and combustion chambers from underneath. At best, however, this inspection is a most inconvenient operation on account of the excessive heat in the confined spaces underneath the ovens.

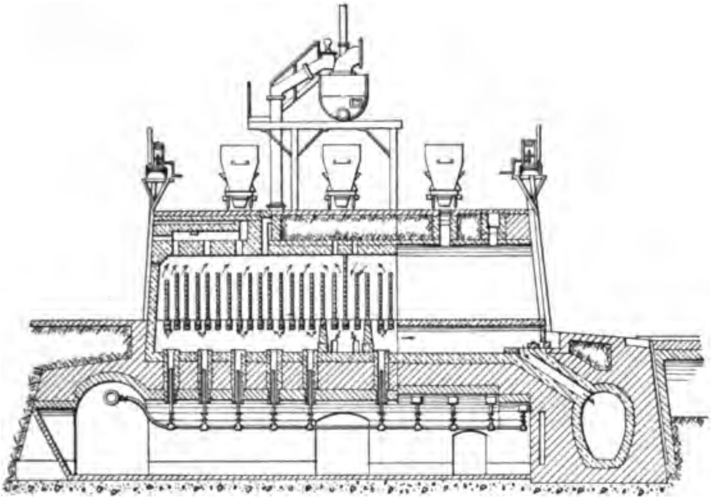

FIG. 24.—The Otto-Hilgenstock by-product coke oven.

The under-burning principle was soon adapted by Hilgenstock to regenerative ovens according to method No. 2 of Meissner's classification. This particular method, however, has not been used in America. The *Iron and Coal Trade Review* (**88**, 275) gives a detailed description of the operation of a German plant of ovens of this type. The oven chambers are 33 ft. long, 7 ft. high, and have a width of 17½ in. at the pushing engine side and of 21½ in. at the discharge side with a capacity of 8 tons of coal.

For the heating of the ovens, the gas from the by-product plant is conveyed through a central main running underneath the entire battery, two small branch pipes being taken off the main directly under the walls of each oven, and connected to nine bunsen burners which burn in vertical flues in each wall. Each wall is divided into nine separate vertical flues, each of which is divided some distance above the nine burners into two smaller flues. The 18 main flues are grouped in four sections, the first and the third of which communicate through the second and fourth with a regenerator flue by way of small openings leading into a horizontal flue running under half of the sole of, say, the left-hand oven. The second and fourth sections communicate in their turn through the first and third sections, with another regenerator flue by way of small openings leading into a horizontal flue running under half of the sole of the right-hand oven. These ways form alternately the burnt-gas outlets and the hot-air inlets, according to which set of burners is in use.

The ovens change every half hour. Taking one wall, for the first half hour the burners in the first and third sections only are alight, and the burnt gases, after rising to the top of the wall descend by the dead flues in the second and fourth sections respectively, pass out through the small openings into the flue under half of the sole of the left-hand oven, and so into the dead regenerator flue and up the chimney. The hot air for the ignition comes to the burners of the first and third sections from the live regenerator flue on the other side of the battery by way of the flue under the half of the sole of the right-hand oven with which these sections are in communication. At the end of half an hour, the burners in the first and third sections are extinguished by cutting off the gas and air, which are then admitted to the burners of the second and fourth sections. The burnt gases now, after ascending the flues of these sections, descend the flues of the first and third sections respectively, and go to the regenerator flue by what was the air-inlet passage for the first half hour. The air for ignition is now admitted from the hot regenerator by what was in the first half hour the burnt-gas outlet.

The two regenerator flues are connected by a common way to the waste-gas chimney, and at their junction is a two-way valve, which allows of the closing and opening of either way at will, this automatically opening or closing the other way. The air burned with the gas is taken from the passage ways, under the ovens, and is regulated by means of sliding shutters placed along the side of the passages. The gas taps of the small branch pipes, and also the air shutters, are all connected, and are opened or closed together. The changing over of the ovens can thus be effected in a few moments.

The American system of end burner and under burners was a modification developed by C. Schniewind. Sections of this modification are shown in Fig. 25. The use of a columnar substructure was designed to facilitate inspection of the ovens from underneath, and the length of the chambers was extended to 43 ft. A plant of this type is in operation at Sharon, Pa. It is interesting to note that at this plant the regenerators were built in vertical form similar to the usual hot-blast stoves for blast furnaces.

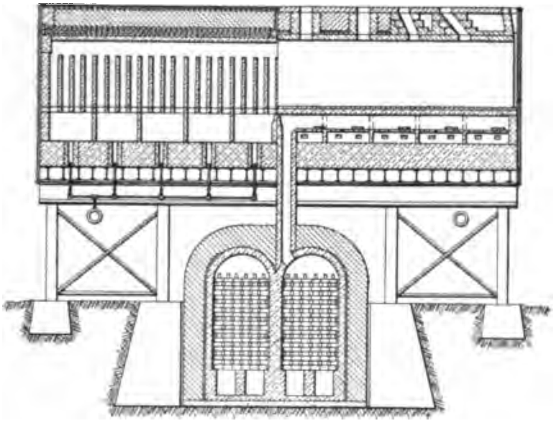

Fig. 25.—Schniewind type coke oven.

THE KOPPERS OVEN

The oven designed by H. Koppers of Essen, Germany, was a decided advance in the evolution of the vertical flue type oven, its especial merit being that it made possible the accurate regulation of combustion and temperature in their essential part of the oven structure. This was accomplished by providing an individual pair of regenerators for each oven, thus making each oven practically an independent unit as far as heat regulation was concerned; and by providing independent burners and draft chambers for each separate vertical flue.

The construction and operation of the Koppers oven will be better understood by an examination of Figs. 26 and 27 which have been made from photographs of a model of a set of these ovens. In Fig. 27 a section of the model has been turned so as to expose a transverse view of the individual regenerator

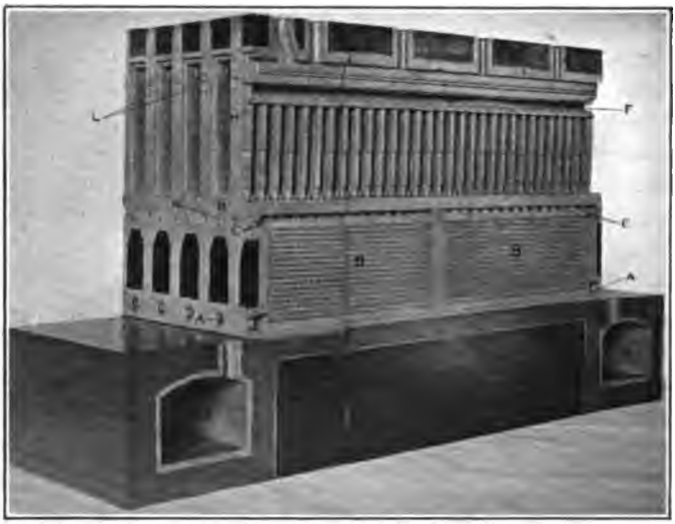

FIG. 26.—Model of Koppers standard cross regenerative by-product coke-oven.

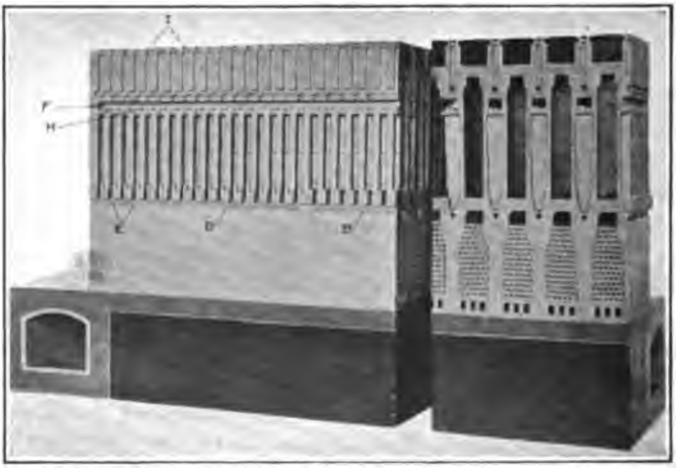

FIG. 27.—Model of Koppers standard cross regenerative by-product coke-oven, showing transverse section through regenerators, flues and oven chambers.

flues, and oven chambers. To follow the process of combustion in the flues let us first consider the reversal period in which the gas is burning in the flues on the left-hand side of the block of ovens. The air for combustion passes through a casting fitted into opening (*A*), and is distributed through the regenerator (*B*), which has been heated in the previous period. Thence it passes up into the several air ports (*C*) communicating with the individual vertical flues. The tops of the air ports are just visible in Fig. 26. The gas is admitted through a burner flue (*D*) and passes up into the several flues through the nozzles (*E*). Combustion takes place upward through the flues and into the horizontal flue (*F*), and the products of combustion pass along this horizontal flue and down the vertical flues in the opposite half of the wall and escape into the opposite regenerators (*B′*) through the air ports (*C′*). They impart most of their heat to the checker work of this regenerator and finally emerge through a casting (not shown in the figure) which connects the opening (*A′*) with the stack flue (*G′*). At the end of this period, which is ½ hr. the process is automatically reversed. This reversal is accomplished in the following sequence:

First, the valves admitting the gas to *D* are closed; then the port admitting air to *A* is closed and simultaneously the damper connecting the flue (*G*) to the stack is opened. Then the connection from the flue (*G′*) to the stack is closed and the connection from *A′* to the air is opened. Finally the gas valves, admitting gas to the burner flue (*D′*), are opened and reversal is complete. The air passes up through regenerator (*B′*) through air port (*C′*) into the flues, and the gas passes up from the burner flue (*B′*) through the nozzles; the products of combustion pass down through the vertical flues on the left-half of the wall and through the regenerator into the stack flue (*G*). It will be seen that the reversing arrangement is designed by shutting off the gas before the air to permit the latter to sweep out the products of combustion before the gas is turned into the opposite regenerator. The sliding brick (*H*) regulate the draft in each individual flue and are manipulated by means of a rod inserted through the short flue (*I*). The upper sliding brick (*J*) serve to close the flue system. The tops of the short flues (*I*) are closed by small iron castings which may readily be removed for inspecting flues. It is also possible to remove and replace each nozzle if necessary by insertion of a long steel rod from the top of the flue. Openings (*K*) and (*L*) are provided to permit inspection of the horizontal flue and regenerator, respectively.

This design permits of the following regulations:

1. Adjustment of the amount of gas admitted into each individual flue by varying the size of nozzle openings.
2. Adjustment of the amount of air admitted into each individual flue by means of a damper brick placed over the air port if necessary.
3. Regulation of the draft in each vertical flue by means of the sliding brick.
4. Regulation of the draft in each individual regenerator by adjustment of a damper (usually of the butterfly type) over the openings (*A*) and (*A'*).
5. Differential adjustment of the draft on the pusher and discharge sides of a battery of ovens by means of dampers in the stack flues (*G*) and (*G'*).
6. Regulation of the stack draft in the battery as a whole by means of a single damper located near the base of the stack, the flues (*G*) and (*G'*) communicating near this point.
7. Differential adjustment of the gas admitted into each separate burner flue by means of cocks or orifices in the pipes communicating between this flue and the fuel-gas main.
8. Differential adjustment of the gas admitted to the pusher and discharge sides of a battery of ovens by means of valves located in the fuel-gas main on each respective side.
9. Regulation of the gas supplied to the battery as a whole by means of a valve located in the main header distributing the gas to the two sides.

This system of regulation is remarkably complete, and its importance can be appreciated by consideration of the necessity of having the charge of coal uniformly carbonized throughout the entire oven, irrespective of the increase in width from the pusher to discharge ends, and also by the necessity of having each oven ready on schedule time, which is indispensable for the maintenance of maximum efficiency on a plant operating to full capacity. Experience has shown it impossible to design an oven that provides for this regulation in its own construction, and the more flexible the system of regulation possible after the plant has been put into operation the more uniformly efficient will be the results. As soon as a battery is put into operation the adjustment of the nozzles, sliding brick, regenerator chambers, and gas valves is begun, and when this is once thoroughly accomplished the operation of the whole battery is readily and satisfactorily accomplished, simply by adjustment of the main fuel-gas valve and stack damper.

The Koppers system has also been adapted to plants where gas is the main product and coke to a certain extent a by-product. Here the main consideration is the production of a high yield of coal gas of the required calorific and illuminating standard, and in order to release for sale the entire yield of gas from the coal it is desirable to provide some other fuel for heating the ovens. An efficient combination is the use of producer gas made from part of the coke including the breeze produced in the ovens. Where it is available, blast furnace gas may also be used or the product from a by-product recovery producer installation. The ammonium sulphate recovery plants are readily operated in conjunction with the coal gas by-product plants. A section of the gas oven is shown in Fig. 28. It differs from the coke oven simply in having a division wall built lengthwise through the regenerator, making in effect a double regenerator for each oven, and in having two lines of ports instead of one from the regenerators into the flues, doing away with the gas duct under the flues. Gas for heating the ovens is made in a central gas producer plant and is cleaned and cooled before being delivered to the ovens. Both gas and air are regenerated and combustion takes place and is controlled as in the coke oven.

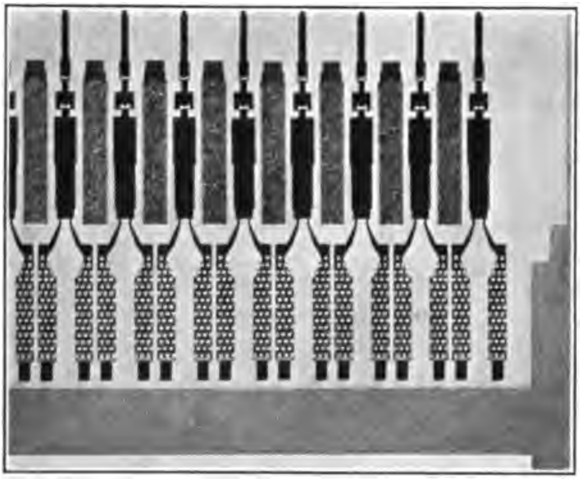

FIG. 28.—Cross-section of Koppers cross regenerative gas oven.

One double regenerator is entirely given over to the preheating of air, the air from one side of the central division wall going to one set of flues and that from the other side, to the next set of flues. The adjoining double regenerator preheats the gas and distributes it in a similar manner, the gas from one side of the division wall going to one side of the oven and that from the other half going to the other side of the oven. By thus having the same gas in both chambers of the divided regenerator, any leaks through the narrow division wall can cause no trouble. Air and gas are separated by the heavy gastight walls under the flues and premature combustion of the fuel gas is thereby prevented.

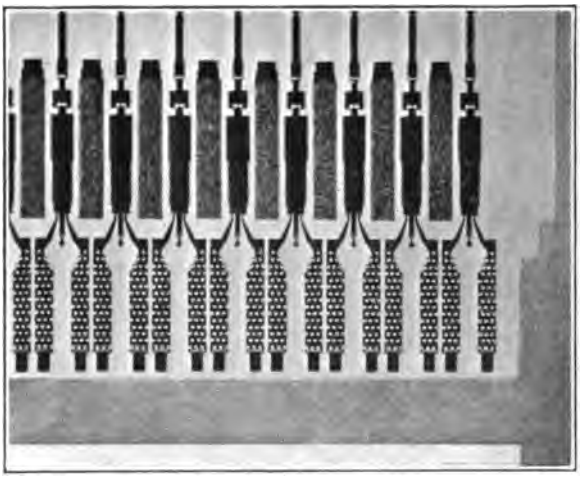

FIG. 29.—Cross-section of Koppers combination oven.

Several plants have also been built in which the principles of the coke oven and gas oven construction are combined constituting a more flexible system which may be operated either with coal gas from the ovens or with producer gas. Wide fluctuations in the amount of gas available for distribution are thus possible with a constant output of coke. The design of the combination oven is readily understood from the section shown in Fig. 29. It differs in the gas oven only in that the burner flue of the coke oven is retained. When the oven is used as a coke oven the divided regenerators are used for air only. When the oven is operated as a gas oven the gas duct is closed and the fuel gas is passed through the alternate regenerators.

Ovens of the Koppers type have been built with capacities ranging from 10 to 16 tons of coal, but the sizes most frequently adopted in present American construction range from 11¼ to 12¼ tons.

The Koppers Company has recently introduced a new type of flue arrangement and construction which is known as triangular flued, because the vertical flues are substantially triangular in shape. This type may be either a by-product coke oven heated with coke oven gas, a gas oven heated with producer gas, or a combination oven which may be heated with either kind of gas. An idea of this new type of oven may be gathered by inspecting Fig. 30 which shows a perspective and sectional view of a battery of these ovens. At the base of each vertical flue is an air port communicating with the regenerator, and a gas nozzle communicating with the usual fuel-gas flue and the cross regenerators are as in the ordinary Koppers oven. It will be seen that, although there appears to be only a single row of flues in each wall, yet there are really two series of flues, one facing toward the oven on the right hand and the other toward the oven on the left hand. Corresponding to these two sets of flues there are two horizontal flues on top of the vertical flues, each pair of horizontal flues corresponding in position with the single horizontal flue in the well-known Koppers ovens. Thus each side of the flue wall has its own heating system and this is accomplished without making the total width of the flue wall any greater than in the usual rectangular flue type. The operation

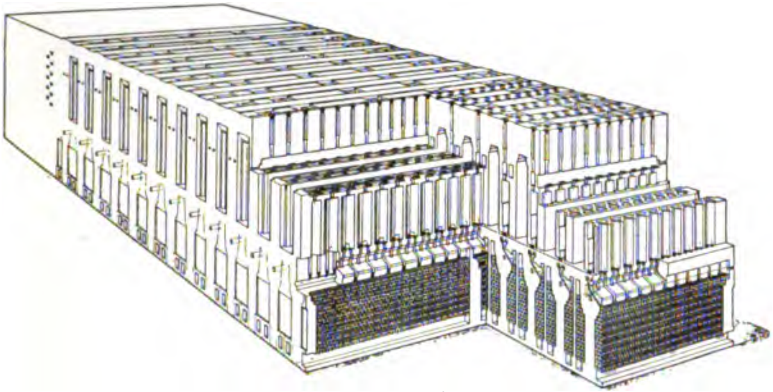

FIG. 30.—Koppers triangular flued ovens.

of reversing the gas combustion is performed exactly the same as in the case of a regular Koppers oven.

Fig. 31.—Top of battery of 106 Koppers ovens, Bethlehem Steel Company, South Bethlehem, Pa.

Fig. 32.—Koppers by-product coke-oven, Dominion Iron & Steel Company, Sydney, Nova Scotia, showing combined pusher, leveler, and door extracting machines.

Among the advantages claimed for this type of construction, are the following:

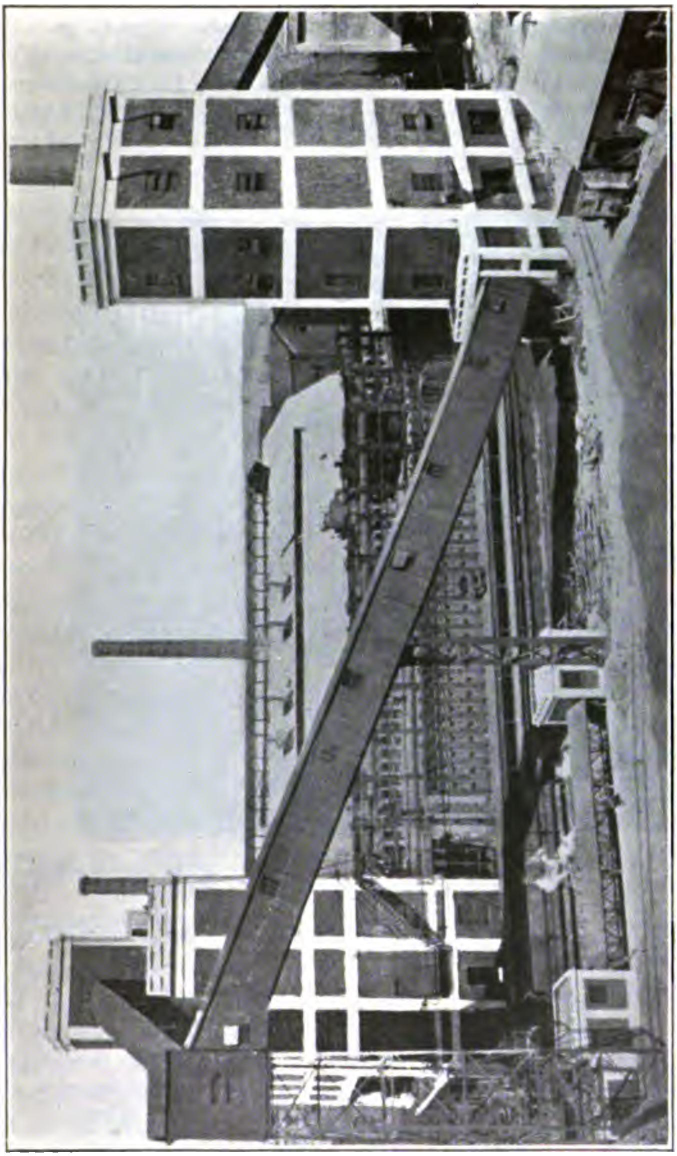

FIG. 33.—Plant of Koppers combination ovens, Providence Gas Company, Providence, R. I.

1. The oven wall is obviously stronger and tighter mechanically than is a wall containing rectangular flues.
2. The heating surface is increased to a considerable extent for each wall.
3. There are more flues, and, therefore, additional points of regulation; therefore fine adjustment of temperature conditions is made possible.
4. Since each face of an oven wall has an independent heating system, it follows that temperature conditions are less affected by pushing or charging an adjoining oven, than is the case with a rectangular-flue construction.

FIG. 34.—Koppers triangular flued coke-ovens under construction.

A battery of five triangular-flued ovens built as combination ovens to use either coke-oven or producer gas was erected as part of the plant of the Minnesota By-Product Coke Co. This battery was put into operation early in 1918 and has been entirely successful and satisfactory from the start. The method of operation and the amount of attention required is the same as in the case of the regular Koppers oven. A battery of 60 triangular-flued ovens is in operation as part of the by-product coke plant of 300 Koppers ovens for the Jones and Laughlin Steel Company, Pittsburgh, Pa. Other installations are being built elsewhere.

PRELIMINARY CONSIDERATIONS AFFECTING BY-PRODUCT COKE OVEN CONSTRUCTION

The various economic considerations that are studied preliminary to building a by-product coke plant include choice of coal, freight rates, market for coke and by-products, quality of coke required, disposition of gas, etc.; but a discussion of these important subjects would be outside the scope of this section. From a technical standpoint, first attention must be given to the kind of coal which is proposed to be coked. If the coal is from a new field, a laboratory examination should be made to determine its coking quality and the yield and quality of the important by-products. The laboratory examination is often followed by a series of oven tests to ascertain the most suitable conditions for the production of coke of the highest grade.

It is important to note that the laboratory examination of coal preliminary to building a plant of by-product ovens is a highly specialized undertaking that can be properly conducted only by the firm that is to construct the plant. Consideration of the great complexity of conditions that affect the behavior of coal when heated, will show that laboratory manipulation must go hand in hand with a large amount of practical experience, if the results are to be of any value. It is not merely enough to test the coal under certain standard conditions and use empirical factors to calculate plant yields. Some coals require different conditions of coking, in order to obtain the best results, and the laboratory treatment must be made to correspond. Moreover, different groups of coals often require different factors, which can only be derived from practical results.

With a knowledge of the characteristics of the coal, the following important points can be settled:

1. Preparation of coal.
2. Dimensions of oven.
3. Arrangement of heating system.
4. Rate of coking.
5. Number of ovens required.
6. Size and amount of by-product apparatus.

There are, of course, many other points to be studied, but these are among the most characteristic and important and should be discussed further.

Preparation of Coal.—Under this head, it must be decided whether or not the coal will require washing, pulverization, or mixture with another coal. The question of washing is decided on the basis of expense saved by reducing the percentage of ash or sulphur in the coke. For example, where the coke is to be used for blast furnace purposes, calculations are made as to freight on ash, extra amount of time needed for fluxing the ash and absorbing the sulphur, extra amount of fuel required for melting the ash plus the additional lime required. Sometimes it is possible to mix two or more coals so as to reduce the percentage of ash, sulphur, or phosphorus to the required extent.

Pulverization is required when two or more dissimilar coals are to be mixed. In other cases, it will improve the structure of the coke, either by preventing segregation of slaty material, or by directly influencing the cell structure. Many difficultly coking coals will not make a satisfactory coke unless finely pulverized.

Mixing with another coal is always indicated where the first coal selected is found to have seriously expanding properties. Mixture is also resorted to when it is desired to improve the quality of the coke, either by strengthening the structure, or by reducing the percentage of ash and sulphur.

Dimensions of Oven.—The most important points are size, width, and taper. Size is determined upon by considering total plant capacity, utilization of gas, and proportional increase of expense required for smaller ovens. Obviously for a given total capacity, the smaller the oven, the more flexible is the system. Small ovens must be built for plants of relatively small total capacity, where gas of uniform quality is desired.

Width of oven is an important factor influencing the quality of the coke made from a given coal. Narrow ovens are especially suited to the coking of high-oxygen coals such as those mined in Illinois and Indiana.

Taper facilitates pushing; a certain amount—ordinarily about 2 in. is desirable for most coals, and the taper is often considerably increased where the coal is known to have slightly expanding properties. In the Koppers ovens of the Illinois Steel Company at Joliet, Illinois, designed to coke a mixture of 80 per cent. Pocahontas with 20 per cent. Klondyke coals, the discharge end of each chamber is 4 in. wider than the pusher end.

The following examples are cited to show oven dimensions and capacities adopted in recent American installations.

The ovens of the Indiana Coke and Gas Company coking 100 per cent. Indiana Coal are 11 ft. 9½ in. high, 39 ft. 1½ in. long and taper from 17 to 15 in. with an average width of 16 in. The capacity is 12½ tons coal per charge.

At the Clairton Coke Plant of the Carnegie Steel Company, there are 768 Koppers ovens coking 100 per cent Klondyke coal from the Pittsburgh seam. These ovens are 37 ft. long, 9 ft. 10⅝ in. high and taper from 19½ in. to 17 in., the average width being 18¼ in. The capacity is 12.5 tons coal per charge.

The Providence Gas Company has 40 Koppers ovens coking 80 per cent Pittsburgh seam coal from Westmoreland County, Pa., and 20 per cent Pocahontas coal. These ovens are 37 ft. long, 9 ft. 10⅝ in. high, and taper from 18¼ in. to 15¾ in., the average width being 17 in. The capacity is 11.6 tons coal per charge.

Arrangement of Heating System.—This must be decided upon, after determining the behavior of the coal in an oven test, its rate of coking, shrinkage, etc.

Rate of Coking.—Coals from different districts are apt to vary greatly in their rate of coking per charge. Thus coals from the Alabama district coke faster at a given temperature than Pittsburgh coals. Frequently it is desirable to coke a given coal at a lower temperature in order to improve the quality of the coke. This, of course, lengthens the coking period.

With ovens of 18 in. average width, coking a mixture of 15 per cent low volatile coal with 85 per cent Pennsylvania or West Virginia high volatile, a coking time of 16 hr. may easily be maintained in regular operation, producing good blast-furnace coke. The 18¼-in. ovens of the Minnesota By-Product Coke Co. operate on 16 hr. coking time with a mixture of 40 per cent. Pittsburgh, 40 per cent. Elkhorn and 20 per cent. Pocahontas coals; but when using 100 per cent. Illinois coal it is found desirable to lower the temperature and lengthen the coking time to about 19 ½ hr. The corresponding rates of coking are 1-in. oven width in 52.6 min. for the former and in 64.1 min. for the latter coal. The ovens of the Providence Gas Co. (17⅛ in. average width) have, during a two-week period of operation, coked a mixture of 80 per cent. Pittsburgh with 20 per cent. Pocahontas coals in 14 hr.—which is equivalent to 1-in. oven width in 49 min.

Number of Ovens Required.—This is determined from the total capacity required, the dimensions of the oven selected, and the rate of coking. In this connection, the number of ovens per battery and grouping of batteries must be decided. Remarkable engineering skill has been developed in taking care of the expansion of the oven brickwork when it is heated, so that plants can be built with many ovens to a battery; but such plants have not the flexibility of operation that is possessed by those having fewer ovens per unit. The largest units so far built in America are those of the Bethlehem Steel Company, Northampton Pa., with 104 Koppers ovens per battery. The Clairton plant of the Carnegie Steel Company, now the largest by-product coke plant in the world, has 12 batteries of 64 Koppers ovens per battery, and is designed for 24 batteries, all told.

Size and Amount of By-product Apparatus.—This can be determined only from the knowledge gained by the preliminary tests of the coal. For example, the number of ammonia stills, the relation of fixed to free sections, and the amount of liquor storage required are based on tests of the yield of free and fixed ammonia and the total percentage of water evolved by the coal on distillation.

BY-PRODUCT COKE-OVEN CONSTRUCTION

The base of a battery of by-product coke ovens consists of a heavy mat of reinforced concrete supporting the stack flues and brickwork. In most instances of Koppers' oven construction, the concrete underneath the stack flues is extended all the way underneath the ovens, and on this heavy base are erected concrete arches situated longitudinally underneath the battery. Over these arches is placed the concrete mat supporting the oven brickwork. The stack flues form part of the whole mass of concrete masonry, but, unlike the supporting arches, are lined with firebrick. With an efficient regenerative system, the temperature of the gases escaping into the stack flues is about 300 to 350°C., which is so low that disintegration of the concrete does not occur and need not be feared.

The lower parts of the regenerators and supporting walls are built of first quality firebrick. In the brickwork above these, it is the rule in American practice to use silica brick throughout, except for the door jambs and for the tops and other parts where temperatures are comparatively low. The use of silica brick in by-product coke oven construction is a distinctively American development and has played an important part in the superiority of the American by-product coking practice over that which prevails in Europe. European practice still adheres to firebrick or quartzite brick. Analyses of different brick used in oven construction are shown in Table XX.

The value of silica brick for by-product coke oven construction is due to the following characteristics:

1. The conductivity at high temperatures is superior to that of clay brick.*
2. The face or wall temperature is much higher than that of fireclay.
3. The action under heating may be calculated with great precision due to its practically constant composition.
4. Although the expansion of silica material when heated to 1,800°F. is comparatively great, the expansion or contraction at operating temperatures, *viz.*, between 2,000°F. and 2,600°F. is practically negligible.

TABLE XX

	Loss on ignition	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Alkalies as K_2O
American silica brick	....	96.25	0.79	0.89	1.80	0.14	0.39
American first quality firebrick.......	0.40	53.59	1.54	42.06	0.30	0.26	2.15
English firebrick.....	....	78.30	2.86	16.18	0.34	0.63	1.53
German quartzite brick.............	0.11	83.15	1.57	13.19	0.37	0.34	1.17

The brickwork is carefully protected from the weather during construction, by means of a temporary shed covering the entire battery. In cold weather fires are maintained in this shed to prevent freezing. The firebrick are laid in fireclay but the silica brick require a highly refractory "silica cement" of which ganister and clay are the chief ingredients.

The expansion of silica brick is equivalent to about ⅜ in. per linear foot and the utmost care must be taken to provide suitable expansion joints, in order to prevent great distortion of the oven structure when heated. Heavy steel buckstays are placed at the end of each oven wall and connected by two tie rods; one passing underneath the wall and the other over the top of the wall. Longitudinal tie rods with turn buckles pass from end to end of the battery and are connected with suitable steel supports.

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* For discussion of the relative thermal conductivity of silica and clay brick, see S. M. MARSHALL, *Met. & Chem. Eng.*, **12**, 74; also G. H. BROWN, *Trans. Am. Ceram. Soc.*, **16**, 382.

As the brick work expands during the heating-up period, the buckstays, tie rods, and supports when properly adjusted bind the whole structure into a solid mass.

The heating-up period preliminary to starting a battery of coke ovens takes at least 6 weeks. About half of this period consists in a slow drying out which is accomplished by means of wood fires; thenceforward, when gas is not available, coke or oil is used to bring the ovens up to operating temperatures. Koppers ovens are provided with small openings leading from the oven chamber into the flues. The coke or oil is burned on specially constructed hearths in the oven chamber and products of combustion pass through the flues to the regenerators and thence to the stack.

In starting a new plant where gas is not available, the ovens are brought to operating temperatures and then coal is charged into the ovens in regular sequence depending upon the heat stored in the brickwork to make sufficient gas to fill the system and burn in the flues.

During all the heating-up period, careful observations of temperatures are made so that the heating is conducted with proper regularity. Expansion measurements are also made and the tie rods suitably adjusted.

BY-PRODUCT COKE OVEN OPERATION

Preparation of the Coal.—The operations used in various plants for preparation of the coal previous to coking may be classified as follows:

1. Washing.
2. Pulverization.
3. Mixing.
4. Compression or stamping.

Whether or not any or all of these operations are requisite, depends upon the kind of coal used and the grade of coke desired. In some cases, the coal may be coked directly as mined. European practice frequently employs compression of the coal, but this is not required in America with the coking coals that are now readily available.

Washing.—In most cases, a low-sulphur and low-ash coke is desired and if the available coal does not possess these qualities, it must be washed A discussion of coal washing does not come within the scope of this section; but the importance of having the coal sufficiently dry before charging it into the ovens must be given emphasis. For satisfactory operation, less than 8 per cent moisture should be present. Higher percentages have a very injurious effect on the brickwork. Previous to washing, the coal always requires a certain amount of crushing and the washed coal is usually coked without further pulverization.

Pulverization.—For the production of uniform high-grade metallurgical coke from ordinary unwashed coal, pulverization is often desirable. It breaks up and distributes the pieces of slate and other mineral material and prevents their segregation in the coke. The presence of large particles of slate is especially injurious to the strength of coke. The slate splits when the coke is quenched and the fracture extends into the coke. Pulverization is obviously advantageous when two or more coals of different character are mixed.

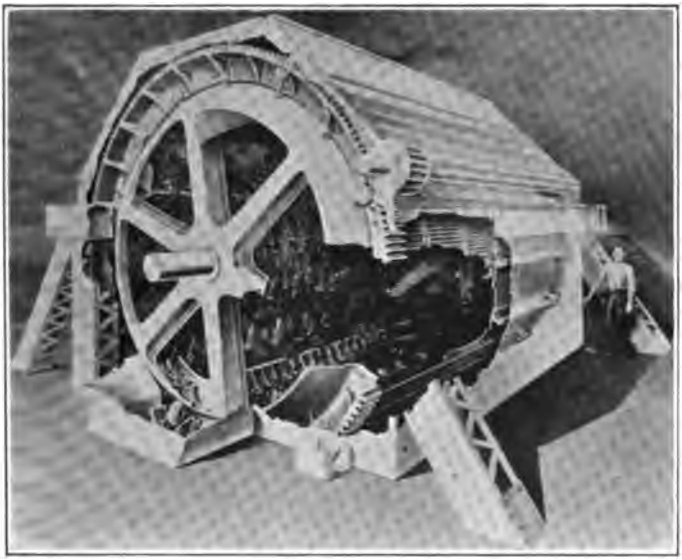

FIG. 35.—Bradford breaker, manufactured by the Pennsylvania Crusher Company.

The degree of pulverization necessary depends upon the nature of the coal and the amount and size of the slaty particles. In present practice where a high volatile coal (*e.g.* from the Pittsburgh seam) is mixed with a low volatile coal (*e.g.* Pocahontas) it is usual to require that not less than 75 per cent shall pass through a screen with ⅛ in. square openings. The cell structure of the coke can be, to a certain extent, controlled by varying the degree of pulverization.

The pulverization is usually accomplished in two stages, first with the aid of a Bradford breaker, and second with a pulverizer; usually of the hammer-mill type. The Bradford breaker (Fig, 35) is a large revolving steel drum with a slightly inclined axis. having a perforated inner shell about 10 ft. in diameter. The shell is arranged with deep longitudinal ribs which raise and drop the coal, breaking it so that the softer coal passes through the perforations while the hard bone, slate and foreign material pass out at the lower end of the breaker. The inclination and diameter of the drum and perforations of the shell are designed to suit the requirements of the coal. The perforations are usually about 2 in. in diameter.

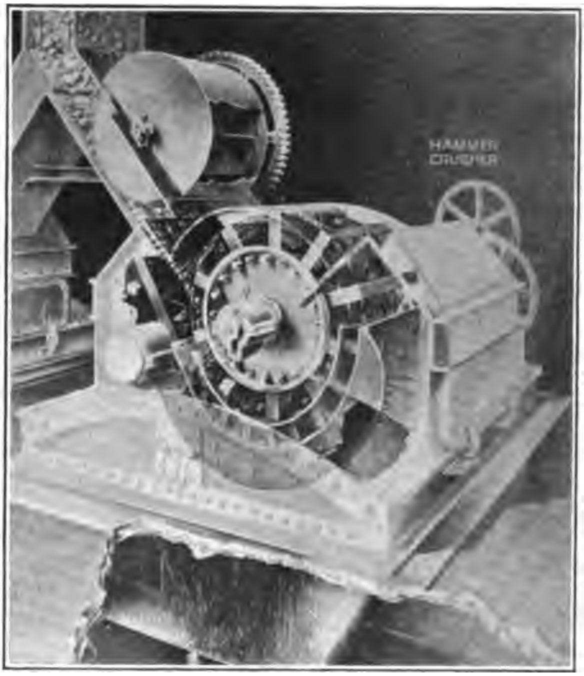

Fig. 36.—Hammer mill for pulverizing coal, manufactured by the Pennsylvania Crusher Company.

The hammer mill (Fig. 36) is made up of several steel bars hung to a common shaft revolving inside a shell, the lower part of which consists of a screen having about 3/8-in. perforations. To each of the bars is hung a row of steel "hammers" (rectangular bars about 12 by 4 by 1 in.). The shaft is revolved at a rate of 500 to 600 r.p.m. and the hammers standing out by centrifugal action pulverize the coal as it is fed into the mill and force it through the perforations of the screen.

Magnetic separators are often introduced in the conveying system between the Bradford breakers and the hammer mills to take out pieces of iron that might otherwise fall into and injure the latter.

FIG. 37.—Coal-mixer for by-product coke plant.

Mixing.—It is almost always true that a better grade of coke may be obtained from a mixture of two coals than can be made from either coal separately. A system enabling the operator to mix two or more coals in regulated and adjustable proportions, affords the best possible means of accurately controlling the quality of the coke produced.

The mixing is sometimes performed simply at the unloading hoppers by dumping the different coals simultaneously; but where the coals have decidedly different characteristics, this practice leads to irregular results. The usual method for thorough mixing consists in feeding the coals from different storage bins by means of belt conveyors simultaneously into a common hopper which may contain mechanically operated paddles for thorough intermixing of the material. The mixing may be accomplished between the Bradford breakers and the hammer mills, or after the latter. Where the coals differ greatly in size and hardness, it is considered best to pulverize completely before mixing.

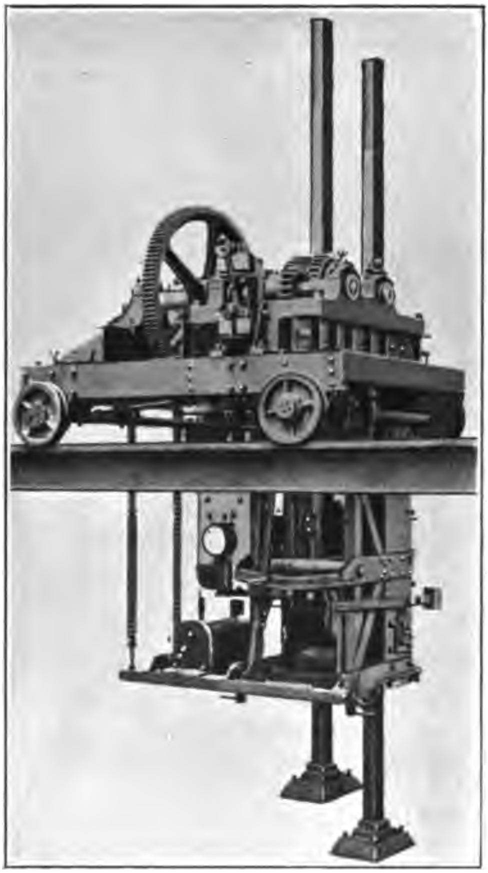

FIG. 38.—German stamping machine for compressing coal charge for by-product ovens.

Compression.—Compression—or "stamping" as it is usually called, was resorted to in some of the older American plants, but has been altogether abandoned in this country. It is, however, common practice in Europe and makes it possible to produce fair metallurgical fuel from coals that would yield a weak porous coke by ordinary methods of treatment.

The stamping machine is usually combined with the pusher. A large steel chamber, forms a mold, matching the oven chamber. Into this mold the coal is fed in layers and compressed by electrically operated stamps. Thus a huge cake is formed which is pushed bodily into the oven by means of the same ram that is subsequently used for discharging the coke. Figure 38 shows a German stamping machine.*

Storage and Charging.—Sufficient storage capacity is usually provided for the prepared coal to operate the ovens 24 hrs. The storage bins are of steel construction and located above the end of a battery at such an elevation that the charging larry may be run underneath.

The charging larry is electrically operated and has four compartments, preferably conical with steep sides to prevent the sticking of wet coal, and corresponding to the four charging holes of the oven. The total capacity of the larry is equal to that of the oven. The bottom of the storage bin is formed of hoppers arranged in rows of four, with suitable gates separately operated, so that each compartment of the larry may be filled with the right amount of coal. Each charge is carefully weighed on a weighing platform located under the storage bin. The practice is to adjust the charges by volume rather than by weight, the object being always to fill the oven to the same level. Too low charges result in losses of products and too high charges may make trouble in the leveling operation or may even seriously interfere with the pushing of the coke. The consequence of this practice is that the weights charged when the coal is wet are considerably less than when it is dry.

Accumulations of old coal are apt to form and hang up on the sides of the storage bin, and it is of great importance to remove these from time to time, because, otherwise, serious damage may result from spontaneous combustion.

Leveling.—The coal as first put into the oven from the charging larry, naturally forms uneven piles with conical tops, which require leveling in order to insure uniform carbonization and prevent obstruction of the gas passage. Neglect of leveling has in

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* This is taken from SCHREIBER,[24] who also gives an interesting detailed description of another type of machine.

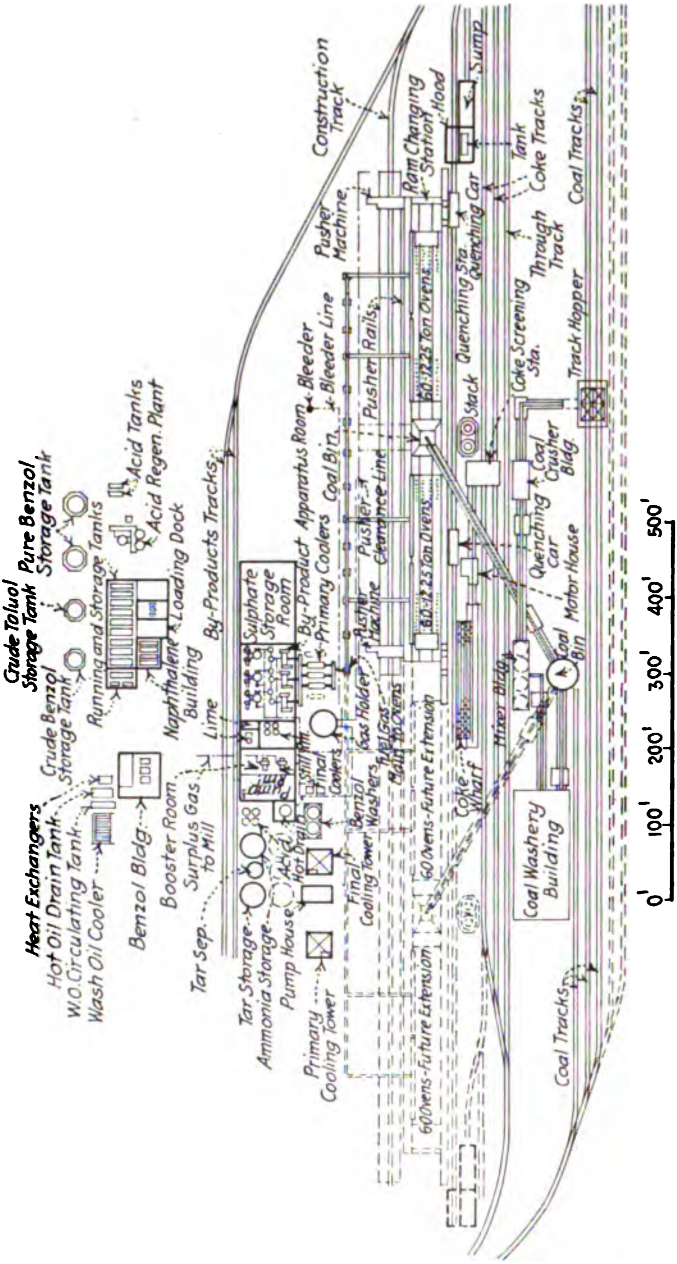

FIG. 39.—Plan of by-product coke plant of Colorado Fuel and Iron Company, built by The Koppers Company.

several instances caused trouble, the coke formed above the level of the discharging door so clogging the oven that the pushing ram could not be operated. The leveling bar is usually operated from the pushing machine, although on certain large plants, such as the one at Gary, Indiana, it has been found convenient to mount it on an independent carriage. The bar is sufficiently long to reach the full length of the oven, and is moved by means of a cable passing over a drum which is operated by an electric motor. Usually the leveling bar is admitted to the oven through a small opening in the oven door; it is run back and forth a number of times until the gas passage is clear, as is shown by the appearance of the flame at the top of the charging holes and standpipe. The bar is then withdrawn, the lids closed and the connection opened from the standpipe to the collecting main.

Collecting Main Operation.—The volatile products from the coke oven pass through a standpipe into a collecting main which is of the type known as a "dry" main, in distinction from the wet main commonly used in gas-retort practice. In the latter, the ends of the standpipes dip below a seal of liquor which is continually being circulated through the main. The pipes are not sealed in the dry main, but a circulation of liquor or tar is maintained sufficient to cool the condensate to a temperature not to exceed 80°C. This circulation serves not only to cool the main; but also to wash out accumulations of pitchy or carbonaceous material. The removal of the latter must also be facilitated by loosening it up with the aid of iron rods introduced through spooning holes in the top of the main.

A large part of the tar and some of the water condense out in the main and are removed through a sealed overflow at the end. The practice now differs, depending upon the type of process that is ultimately employed to recover the ammonia; but in any case, the uncondensed gases and vapors are pumped out of the main by exhausters through suction mains which convey them to the by-product recovery apparatus proper. The suction is maintained at such a point that the gas in the oven chambers is as nearly as possible under atmospheric pressure. This requires a very delicate adjustment of pressure in the collecting main, the variation of a single millimeter of water-gage pressure making a considerable difference in the amount of leakage through the oven walls. The regulation is accomplished by automatic governors on the exhausters, and frequently by valves on the suction mains, electrically operated and controlled by transmission of pressure fluctuations in the collecting main.

Gas Separation.—Most of the older plants that sell their surplus gas for illuminating purposes, have systems for gas separation. Each oven is connected through its standpipe to a short header opening into two parallel collecting mains. Valves are arranged in the header so that the oven gas can be made to pass into either of these two mains.

From the collecting mains through the by-product recovery apparatus and beyond, there are two separate systems for handling the gas. This makes it possible to collect the "rich gas," which comes off in the first part of the coking period, separate from the "lean gas" which comes off in the last part. The rich gas, being high in hydrocarbons, illuminants, heating value and illuminating value is well suited for sale where local requirements demand high heating value, while the lean gas is excellently adapted for heating the ovens.

Since the heating of the ovens is of prime importance in the operation of the plant, it is customary to gage the separation process by the rate of consumption of lean gas, ovens being connected in the proper sequence with the lean main at such a rate as to keep pace with the consumption. A by-pass connection is always provided so that if necessary some of the rich gas may be put into the lean gas system, or *vice versa.*

The present tendency in building by-product coke plants for gas manufacturing purposes is to eliminate gas separation, because it is coming to be recognized that the old standards of high candle power and high heating value are expensive and unnecessary, and that straight coke-oven gas from modern ovens is entirely satisfactory.

Pushing.—On the older by-product coke plants it used to be the practice to treat each oven as an independent unit, inspect it from time to time and push the coke when it appeared to be ready, irrespective of any regularity of sequence. The regulation of the heating of modern ovens, has, however, attained such a degree of perfection that a whole battery can be operated at a uniform temperature throughout and it is possible, using a constant coal mixture, to determine to the minute without preliminary inspection when each oven is ready to push. A regular schedule or sequence of pushing is, therefore, arranged. Usually the ovens are grouped so that every tenth oven along the battery is pushed, each group of ovens taken by the pusher at a single run from one end of the battery to the other being called a *Series*. Thus in a battery of 60 ovens, the "four-series" comprises the ovens numbered 4, 14, 24, 34, 44 and 54. The "10-series" comprises ovens numbered 10, 20, 30, 40, 50 and 60.

The principle to be observed in arranging the order in which the different series are taken is that newly charged ovens should be kept as far apart as possible. Thus it would not do, after pushing oven No. 54 of the "four-series" to come back and push oven No. 5, beginning the "five-series" because obviously the introduction of a fresh charge in the oven adjoining oven No. 4 which has only recently been charged would produce an undue cooling effect on the flue wall between these two ovens.

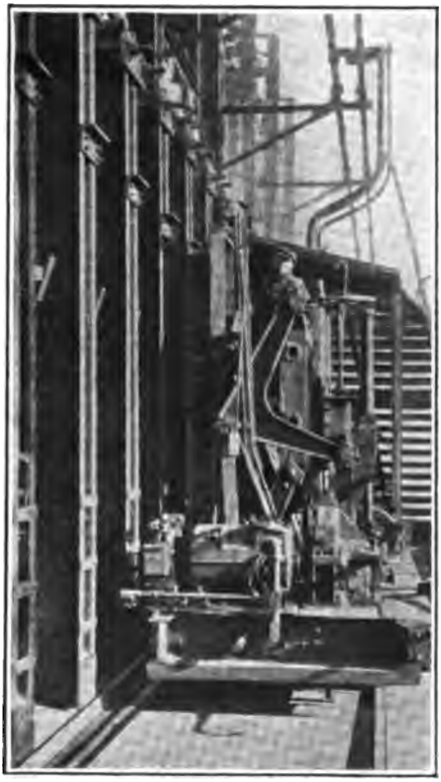

Fig. 40.—Koppers door-lifting machine and coke guide.

The following schedule for a battery of 70 ovens complies with this principle.

Order of pushing	1	2	3	4	5	6	7	8	9	10
Series	1	3	9	5	7	2	10	4	8	6
First oven	1	3	9	5	7	2	10	4	8	6
Second oven	11	13	19	15	17	12	20	14	18	16
Third oven	21	23	29	25	27	22	30	24	28	26
Fourth oven	31	33	39	35	37	32	40	34	38	36
Fifth oven	41	43	49	45	47	42	50	44	48	46
Sixth oven	51	53	59	55	57	52	60	54	58	56
Seventh oven	61	63	69	65	67	62	70	64	68	66

FIG. 41.—Door extractor, coke-guide and quenching-car.

A short time before an oven is scheduled to be pushed, it is "dampered off," *i.e.*, the connection with the collecting main is closed and the top of the standpipe is opened so that any remaining gases pass out into the air, where they quickly catch fire. At the same time, the oven lid farthest away from the standpipe is opened, permitting a circulation of air along the top of the oven and up the standpipe. This has the effect of loosening and burning off any carbon that may be adhering to the brickwork.

The electrically operated door-extracting machines are now brought opposite the oven. These machines are sometimes suspended from overhead rails and more frequently travel on rails running along the walks on either side of the battery.* On the pusher side the door extractor is often made part of the pusher machine. On the coke side, the door machine hauls the coke guide, which is a cage mounted on a truck in such a way that, when connected with the buckstays, it forms a short continuation of the oven chamber, preventing the coke from spilling over the walk before it reaches the quenching car.

The doors having been removed and the luting mud shoveled away, the coke guide is adjusted and the pusher brought into position on the opposite side. In all modern plants, the hot coke is pushed directly into a steel "quenching car," hauled by an electric or steam locomotive. The quenching car has a sloping bottom covered with heavy steel plates and doors that are raised or lowered by compressed air from the locomotive.

Quenching.—The quenching must be rapidly performed with an excess of water, and enough heat must be retained in the interior of each piece of coke to evaporate most of the water that penetrates into the exterior. Rapid quenching with a large excess of water is effective in extinguishing the combustion which of course begins immediately upon the exposure of the mass of hot coke to the air; but, as may readily be conceived, it is very difficult to accomplish uniformly. If the coke is drenched sufficiently to extinguish all "hot spots," its average moisture content will be far too high. Consequently where a coke with the lowest possible percentage of water is desired, operators have found it best to give the coke a short initial quenching (of about 40 sec. duration) and then extinguish any "hot spots" by hand ("spot-quenching").

In some cases, the initial quenching is accomplished by passing the car back and forth under a heavy stream of water from a single spout; but this device is now superseded by the "quenching tower." This is a rectangular tower about 50 ft. high, built of brick or concrete and open at the top. In the upper part are arranged several rows of perforated pipes connected to a water-supply tank of about 20,000 gal. capacity. By turning a valve near the track level, a uniform, heavy shower is produced. The valve is often arranged to be operated by the engineer of the

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* In some older plants, the doors are sometimes raised by cables. In a few cases where the ovens are small, hinged doors are used.

quencher locomotive. The great volumes of steam produced in the quenching operation are confined by the tower and issue at the top at such a height as to obviate the nuisance that would result if no such arrangement were provided.

About 600 to 650 gal. of water are required per ton of coke at each quench, and 100 to 110 gal. of this evaporate. It is common practice to use the waste water from the gas coolers in the by-product building for quenching. The waste water from the quenching operation carries a quantity of coke breeze, so provision is usually made for a settling basin in which this material may accumulate and be removed from time to time by a crane bucket.

FIG. 42.—Coke-quenching station and wharf.

Door Luting.—Before proceeding with a description of the coke-handling system, we should return for a moment to the empty oven from which the coke was pushed.

The doors are immediately replaced and luted. The luting mud is prepared by grinding up a mixture of fresh clay with old luting material swept up from the walks, and is carried on a special "clay carrier." This contrivance is rolled along the walks and permits the workmen to climb up and apply the mud thoroughly over the door joints.

Efforts have been made to devise self-sealing doors that would dispense altogether with luting, but these have not so far met with success. The luting is performed very rapidly by hand, and no successful mechanical luting device has so far appeared.

The oven is sometimes charged directly after the next oven in series has been pushed; but on some plants it is the practice to leave each oven empty for about half an hour, to complete the burning off of accumulations of carbon.

The Coke-handling System.—The quenching car with its load of recently quenched coke is allowed to drain for a minute or so, and is then brought to the coke wharf and emptied. The wharf is about 15 ft. wide and the bottom, lined with heavy steel plates, like the quenching car, slopes down to a belt conveyor that runs along its lower edge. Gates formed of curved steel rods about 4 in. apart, hold the coke on the wharf and are operated by hand to regulate the feed onto the belt. The wharf provides a storage place where the coke may be inspected and any "hot spots" quenched with a minimum amount of water. It has a capacity to hold the coke from two to four ovens so that the oven operation may proceed steadily, undelayed by minor changes or repairs in in the screening system.

The methods of handling the coke after it leaves the wharf depend principally upon whether the bulk of the material is to be used as blast-furnace fuel, or whether the plant sells a considerable proportion of its output to the foundry and domestic market.

Blast Furnace Screening Practice.—There is a considerable difference of opinion among furnace men as to how much of the small sized coke should be screened out. At some plants, the screenings run as high as 1¼ in. but this is rather extreme, and the majority prefer to take out material of less than ¾-in. size. The screenings are usually rescreened into two sizes, *viz.* "domestic coke" and "breeze." The coke products usually made at a blast-furnace plant are as follows:

	Size, inches	Usual percentage of total coke.
Furnace coke................	Over ¾	92
Domestic coke...............	½ to ¾	2
Breeze......................	Under ½	6

The screening system for blast furnace coke is sometimes very simple, consisting merely of stationary bar screens over which the coke is dumped and allowed to run directly into railroad cars. In some plants shaking screens are used, while in others the coke is passed through revolving screens.

In the plant of the Carnegie Steel Company at Clairton, Pa., the coke is passed directly to the cars over a stationary-bar grizzly screen made up of hard-iron bars set with ⅞-in. top and 1¼-in. bottom. There are six sets of bars, each bar 24 in. long. The fines passing through the grizzly screen are rescreened through a rotary screen with ¾-in. wire-mesh openings.

Foundry and Domestic Screening Practice.—This involves a much more complicated screening system. The usual sizes of the various commercial products are as follows:

Foundry coke	over 2½ in.
Egg coke	1⅞ to 2½ in.
Stove coke	1⅜ to 1⅞ in.
Nut coke	¾ to 1⅜ in.
Pea coke	½ to ¾ in.
Breeze	under ½ in.

These sizes, however, vary somewhat in different plants. Sometimes the stove coke is merged with the egg and nut sizes. Different types of screens make a considerable difference in the average size of each product. For a straight domestic market, the larger sizes are crushed and screened.

Following are examples of coke products made from a common American coal mixture:

	Per cent of run of oven coke, screened for foundry and domestic	Per cent of run of oven coke, crushed for domestic
Foundry	43	
Egg	25	18
Stove	13	37
Nut	11	19
Pea	4	7
Breeze	4	19

The following description of the coke-handling system of the Seaboard By-Product Coke Company* shows a good example of modern practice in a large plant designed with the utmost flexibility of operation.

The plant has 165 Koppers' ovens with an aggregate capacity to coke 3,000 tons coal per day, yielding about 2,200 tons coke per day.

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* By D. MacArthur, *Gas Age*, Jan. 1, 1919, 1.

The quencher car can dump on either of two 15-ft. by 85-ft. wharves, each of which is of three ovens capacity. One feeds via a 36-in. belt, a combination rotary grizzly separator for foundry and furnace, at the rate of 100 tons per hour, the screened coke loading directly to cars by means of a 50-ft. 42-in. conveyor which can run out to a box car loader or in and down to hopper and gondola cars. The fines from this grizzly can go direct to stock, to domestic screens via No. 2 wharf, or by passing the latter to stock via the return stock route. No. 2 wharf feeds No. 2 grizzly at the rate of 150 tons per hour, sending foundry, furnace, or run of oven to boat or wagon, and the fines through a 100 tons per hour crusher, or direct to screens.

Fig. 43.—Coke screens, revolving grizzly and conveyor belt.

By-passing this grizzly, run of oven can be sent crushed or straight to two 150-tons per hour Bartlett Hayward "tossing" screens, which drop the breeze through 5/8-in. round perforations into a 150-ton reinforced concrete bin, pea through 1-in. to 150-ton, nut through 1½-in. to 150-ton, stove through 2¼-in. to a 250-ton, and egg over into a 250-ton bin. Screened domestic can be run to stock or rescreened and loaded to hopper, gondola or box cars, or over rescreen and belt scale to wagons or boat, via barge loader. The barge loader consists of a movable boom belt mounted on carriage with a 180° rotation.

The 13 coke conveyors use 4,250 ft. of belting, average 27,500 kw.-hr. per month and have a total horsepower demand of 245. Several transfer chutes link the coal handling to coke. The belt system is so flexible it is entirely possible to unload coal or coke from one barge, weigh it twice by belt scales and reload to another barge or to wagons; or again to unload, weigh once and reload to hopper, gondola or box cars, or to wagons; or again to unload from cars either coal or coke and reload as stated. On coke handling the following operations may be simultaneous:

First—Foundry, furnace, or run of oven to hopper, gondola or box cars from one wharf.

Fig. 44.—Box-car coke loader.

Second—Foundry, furnace, or run of oven to barge or wagon from another wharf.

Third—Fines from foundry or furnace, separated by the rotary grizzly, either direct or through crusher to domestic screens.

Fourth—Screened domestic to hopper, gondola or box cars to wagons or to stock.

The coke yield averages about 75 per cent and in loading averages 44 per cent foundry, 28 per cent egg, 14 per cent stove, 6 per cent nut, 2 per cent pea and 6 per cent breeze; or 84 per cent furnace, 6 per cent egg, 4 per cent stove, 2 per cent nut, 1 per cent pea and 3 per cent breeze.

THE BY-PRODUCT COKE OVEN AS A SOURCE OF GAS AND THE USE OF PRODUCER GAS FOR OVEN HEATING

The modern regenerative by-product coke oven, handling the usual coals, requires for the coking operation only 40 per cent. of the heating value contained in the total gas evolved, leaving 60 per cent available in the surplus gas. In several cases this has reached 62 per cent. The character of the coal is, however, an important consideration. The heat required to effect carbonization appears to increase with the percentage of oxygen in the coal. Thus the coals of Illinois and Indiana may require as high as 1,500 B.t.u. per pound as compared with 1,150 to 1,250 B.t.u. for the Eastern coals.

FIG. 45.—Arrangement for firing Koppers combination ovens with either producer gas or coke-oven gas.

It is generally recognized that American industry has led the way in the construction of by-product coke plants for the primary purpose of furnishing gas for industrial or domestic consumption. In 1917, by-product coke oven gas sold to domestic and industrial consumers amounted to more than one-third of the entire amount of artificial gas marketed in the United States. This includes any gas sold by coke plants to concerns operating under the same management as well as gas sold to outside concerns. The bulk of such gas is consumed in the iron and steel industry.

We are, however, more particularly interested in gas sold for domestic and industrial purposes outside of the iron and steel industry. The present annual consumption of this sort is approximately 40,000,000,000 cu. ft. and the indications are that this amount will be greatly increased during the next few years. The following cities obtain either all or a large part of their gas supply from by-product coke ovens:

Baltimore, Md.
Boston, Mass.
Camden, N. J.
Detroit, Mich.
Indianapolis, Ind.
Jersey City, N. J.
Joliet, Ill.
Milwaukee, Wis.
Newark, N. J.
Providence, R. I.
St. Louis, Mo.
St. Paul, Minn.
Terre Haute, Ind.
Toledo, Ohio

The following advantages are claimed for the by-product coke oven over the gas retort for the large-scale manufacture of coal gas:

1. The quality of the gas produced is equal, if not superior, to that of the gas retort.
2. The coke is of superior quality and commands a better price and wider market.
3. There are the following advantages with relation to the by-products:
    (*a*) The yield of ammonia from the same coal is greater.
    (*b*) The quality of the tar is better especially with respect to higher content of oils and lower percentage of free carbon, except possibly in comparison with the vertical retort.
    (*c*) The yield of benzols is greater.
4. The coal and coke are handled mechanically in relatively large masses. This results in great economy in labor in comparison with gas retort operation, which, in many cases, requires much hand labor of a particularly arduous and unpleasant character. Where mechanical handling machinery and other labor saving devices are installed in the retort house, the items of interest, depreciation, and repairs are excessive in proportion to the tonnage handled.
5. The plant is much more compact and occupies less ground space than the best designed retort plant of equal capacity.
6. The heating efficiency is greater.
7. The life of the plant is longer and repair charges are less.

It has been stated in a previous chapter that the present tendency in building by-product coke plants for gas manufacturing purposes is to eliminate gas separation. The gas which gives the best service to the consumer for the investment and operating expense required is straight coke-oven gas from which the benzols have been removed. With properly selected coals, the modern by-product coke plant will produce straight gas having a heating value of 560 B.t.u. per cubic foot after removal of benzols. Such gas is excellently adapted for all domestic and industrial purposes, and it is becoming recognized that any local standards that demand gas of higher heating value are indefensible from an economic standpoint.

If the benzols are not extracted, the straight gas will have a heating value of 585 B.t.u. per cubic foot. If local requirements call for a higher heating value, gas separation will be necessary and with this system it is easy to produce surplus gas of over 600 B.t.u. per cubic foot. The heating value may be still further increased by extracting the benzols from the lean gas and using them to enrich the rich gas. Apart from any arbitrary local standards, however, gas separation is not worth the additional investment and expense required. Moreover, the removal of the benzols is, in most cases, so profitable that failure to effect it involves unnecessary waste.

In addition to plants that have been built primarily for manufacturing gas, a considerable number of other plants operating in connection with blast furnaces and steel plants are selling more or less of their surplus gas to cities or industrial consumers. At present, all the by-product coke ovens operating in conjunction with iron and steel plants are heated with their own gas. In the case of merchant blast furnaces producing their own by-product coke very little of the surplus coke oven gas is needed on the plant and practically all may be sold to outside concerns or to municipalities. On the other hand, in the case of a complete steel plant comprising blast furnaces, open-hearth furnaces, rolling mills, and by-product coke ovens, all of the surplus gas can advantageously be used in addition to the surplus blast-furnace gas for the manufacture and heating of steel or for the production of power.

All such plants, however, can release for sale the high-grade gas that is now being used for oven heating if they install a type of oven adapted to heating with producer gas. The demand for high-grade gas is increasing to such an extent as to offer strong inducement to iron and steel concerns to use producer gas for heating their coke ovens so that they can sell the equivalent of coke oven gas. In any case where the production of gas is the principal consideration or where sufficient profit may be made from the sale of that part of the gas which is ordinarily used for oven heating, it is desirable to build the plant so that producer gas can be used at any time. The practice of heating ovens with producer gas was introduced by Koppers in the gas-oven plant of the city of Vienna which was put into operation in 1908. The Koppers gas oven and combination oven has been described on page 151.

In considering producer gas-fired gas ovens, we should distinguish between the heating system used in these and the system employed in heating benches of gas retorts. These latter are also fired with producer gas, but the producers are built in and form part of the bench structure while with the gas ovens the producers are built as a separately operated independent central plant.

C. J. Ramsburg[28] has compared the efficiency of the carbonization process, using the built-in producer, with that of the gas oven heated by clean gas from a central plant. From a test on the producer gas-fired ovens of the Vienna plant, he finds the overall heating efficiency of the latter carbonizing system to be 50 per cent. as compared with 39 per cent. for a gas-retort plant. He makes the following criticisms of the built-in producer used in retort practice:

> "In the first place, it is usually so designed that it is exceedingly difficult to discharge the hot coke into the producer so as to insure a level fire, and one of uniform texture. This means an over-use of a portion of the fire and the resulting gas is of very variable constitution. If this feature is to be overcome, it is usually necessary to use cold coke.
>
> "The fire temperature is such that in certain zones fusion of the ash occurs and interference with free, uniform flow of primary air takes place, so that the amount and quality of the gas produced varies from time to time.
>
> "The producer is charged with fresh fuel at long time intervals, making the depth of fire a constantly varying one which also means a variation in quantity and quality of gas.
>
> "Natural draft is depended upon for combustion. This means that any interference with the primary air supply by means of accumulation of ash or clinker, or any weakness in the fire due to poor fuel distribution

immediately reacts upon the secondary air supply in a reverse manner for efficiency, a decrease in producer gas corresponding to an increase in secondary air, thus making it impossible to preserve a high and uniform efficiency of combustion.

"Another defect of the "built-in" producer is the large amount of carbon removed with the ash. This is due to poor conditions of combustion in the base of the fire. It is not an infrequent occurrence to find that the ash from such a producer contains 25 per cent. of carbon.

"The built-in" producer takes no account of the dust passing from the fire into the combustion chamber and into the flues. This dust is of a composition, similar to the ash of the coal used, and for the most part has a fusing temperature between 2,200°F. and 2,600°F."

He lists the following advantages of producer gas-fired ovens of the Koppers type:

1. The oven is heated with clean, cold gas from an extraneous source.
2. This gas is made in a producer plant so arranged as to give high efficiency and to use the coke breeze made in the ovens and during coke handling.
3. The quantity of this material necessary together with the good coke used amounts to only 11 per cent to 12 per cent of the weight of coal carbonized.
4. The producer gas is capable of exact regulation for each oven.
5. The oven is heated by 30 vertical flues, the heat in each one being capable of adjustment.
6. Ovens are charged to a point higher than heat is applied, thus protecting the gas from over-heating on its passage above the coal.
7. All heated walls are in contact with conducting material on which and through which the heat is being used, thus reducing the temperature below the point of injury to the gas.
8. By use of regenerators, heating both secondary air and producer gas, the temperature of the outgoing stack gases is reduced to below 500°F., thus giving a high thermal efficiency of carbonization.
9. By handling coal and coke in large masses, labor is decreased and mechanical operation used to great advantage.
10. Gives a hard coke which can compete with anthracite coal at similar prices. Such coke contains nearly 10 per cent more fixed carbon than anthracite sold for domestic purposes and will stand handling with little deterioration.
11. Cost of the complete plant including producers is as low as any other form of efficient coal-gas apparatus.
12. Being constructed of silica material, the life of the plant is very great and repairs reduced to a minimum.
13. The advantage of complete heat control in the ovens makes it possible to raise and lower the coking time quickly and efficiently, thus permitting the amount of coal carbonized and the consequent gas output to be varied with the seasons and as demands are made for gas.

14. Carbonization in gas ovens gives maximum yields of high quality gas together with high ammonia yield, high tar yield of maximum value and an excellent coke.

In America, the Semet-Solvay Company has used producer gas to heat some of its recuperative ovens. In the Semet-Solvay plant at Chester, Pa., this was done in order to recover more gas for sale than was possible with the recuperators. The producers are four in number, of the Taylor type, equipped with waste heat boilers. When the producers are all in operation, they, together with the main boilers on the main waste-heat flue of the ovens, furnish the entire steam required by the plant.*

The Koppers oven is the only regenerative oven that has so far been designed to operate with producer gas. The first plant of Koppers combination ovens built in America was that of the LaClede Gas Light Company, at St. Louis, Missouri, put into operation in 1915. This plant has not yet been operated with producer gas. The first plant of Koppers ovens to use producer gas was that of the Providence Gas Co., at Providence, R. I. which started operation in January, 1919. The gas for this plant is furnished by five Wellman-Seaver-Morgan Company producers operated either on bituminous coal or coke breeze and designed to be used either with by-product recovery or without. The ovens form a very flexible system with respect to gas production which is of great advantage in view of the wide fluctuations of demand for domestic gas. Part or all of the ovens can be heated with producer gas manufactured either from coal or from coke and the operation and production can be adjusted to a wide variety of conditions. It is stated† that the experience of 6 months continuous operation has shown that the uniform heating and convenience of operation are in no wise disturbed by the simultaneous use of the two radically different types of fuel gas. The regulation of temperature conditions with producer gas is accomplished with even greater ease than when using coke oven gas.

The plant has been operating regularly on 20-hr. coking time, but 10 of the ovens have been operated on producer gas for 2 weeks continuously at 14-hr. coking time and for 4 weeks at 14½-hr. coking time, with highly satisfactory results as regards quality of gas, coke, by-products, and efficiency of heating.

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*J. D. Shattuck, *Gas Age*, January 1, **1919**, 7.

† Report of the Carbonization Committee, Amer. Gas Assn., **1919**.

The 14-hr. coking time corresponds to an average rate of carbonization of 1 in. oven width in 49 min.—a remarkably fast performance. Analyses of products of combustion showed 17 to 18 per cent. carbon dioxide with about 1 per cent. of oxygen and practically no CO. The temperature of the stack gas was about 350°C.

BY-PRODUCTS AND THEIR RECOVERY

On pages 82-92 we have studied the various phenomena of the carbonization of coal in so far as they are related to the formation of coke. We may now, preliminary to a description of the apparatus used for by-product recovery, examine briefly the commercial value and the conditions of formation of the by-products. This is a subject in itself worthy of a separate volume and it is almost impossible to treat it adequately in the short space that can be allotted here.

The commercially important primary by-products of the coking of coal are:

1. Gas.
2. Tar.
3. Crude naphthalene.
4. Ammonia.
5. Benzols.
6. Cyanides.

The first five are the products actually recovered and marketed on a complete by-product coke plant, the cyanides being usually neglected in present installations. Of course if the list were extended to the secondary by-products made from these materials, it could be greatly multiplied.*

The yields of the primary by-products from a mixture of 85 per cent high volatile, 15 per cent low volatile coal, such as is now commonly used to make first class by-product coke in the Middle States district, are about as follows:

Products	Yield per Ton Coal
Surplus gas (560 B.t.u.)	6,000 cu. ft.
Tar (including naphthalene)	9.5 gal.
Ammonium sulphate	25 lb.
Benzols	4 gal.
Sodium cyanide	1.8 lb.

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* Sulphur, which is often recovered as a by-product of gas purification, might also be included in the list.

According to Frank Marquard,[44] the actual yields obtained by the Clairton plant of the Carnegie Steel Company, operating on 100 per cent high volatile coal, are as follows:

Products	Yield per net Ton Coal
Surplus gas (575 B.t.u.)	6,000 cu. ft.
Tar	12 gal.
Ammonium sulphate	25 lb.
Pure benzol	2.3 gal.
Pure toluol	0.57 gal.
Crude light solvent	0.22 gal.
Crude heavy solvent	0.11 gal.

The character and quality of each of the by-products are profoundly influenced by the kind and condition of the coal used and by all of the various factors taking part in the process of carbonization. We must bear in mind the essential features of the coking process, *viz.*; the formation of the fused zone and the gradual advance of this zone toward the center of the oven. The zone constitutes a diaphragm impervious to any passage of the gases inward toward the coal from its outer surfaces, the volatile products passing through the hot coke already formed and up along the walls of the oven, thereby undergoing important secondary decomposition. The amount of secondary decomposition increases as the coking progresses, because the gases have to travel over a greater and greater extent of hot surfaces, and because the temperature of the surfaces necessarily increase as the coking progresses.

Tar Formation and Characteristics.—There is an important difference in the character of the tar produced by low- and high-temperature distillation of coal.[23] If the temperature be comparatively low the hydrocarbons formed belong principally to the paraffin and olefine series. The tar is thinner and fluid and contains very little free carbon. Of the oxygenated compounds the creosotes predominate and the tar has a characteristic acid reaction, even acetic acid being present. As the temperature of distillation is increased the paraffins soon disappear. The olefines persist to a certain extent, but the bulk of hydrocarbons partake more and more of the nature of the aromatic series. Such compounds as benzene, naphthalene, anthracene, phenanthrene, etc. predominate. Creosotes are diminished in quantity and phenol proper (C_6H_5OH) is increased to a marked extent. The acid action disappears and the tar assumes a basic character (on account of the presence of pyridine). With the molecular decomposition and condensations involved, hydrogen is separated and free carbon deposited. The tar is much thicker and heavier and if produced at extremely high temperatures may, when cooled, be practically solid. The quantity of tar appears to increase up to a certain point, and then decreases. Börnstein[3] and Christy[*] found evolution of tar the most abundant between 300 to 400°C. and to decrease considerably above 500°C. The tar produced in gas retorts contains a much higher percentage of free carbon than that made in by-product coke ovens and shows evidences of extensive decomposition, due to prolonged contact with highly heated surfaces.

The kind of coal used, of course, has a great influence on the composition of the tar. According to Bunte[†] the yield of tar increases with the percentage of oxygen in coal. The tars from the more highly oxygenated coals are thinner than those from the richer bituminous coals and partake of the character of the products of low temperature distillation of the latter.

The tar produced in the operation of a typical plant gives the following analysis:[44]

Moisture	1.25 per cent	
Specific gravity	1.156 (at 15°C.)	
Viscosity	140 at 60°C. (Saybolt method)	
Free carbon	4.25 per cent	
B.t.u. per pound	16,200	
Sulphur	0.55 per cent	
Distillation:		
Light oil (0–170°C.)	0.20 per cent	
Carbolic oil (170–230°C.)	9.60 per cent	3 per cent carbolic acid; 6 per cent cresylic acid
Creosote oil (230–270°C.)	10.20 per cent	
Anthracene oil (270–350°C.)	23.00 per cent	
Pitch (at 350°C.)	57.00 per cent	
Coke residue (at 1,200°C.)	17.20 per cent	

Benzol.—The question as to the conditions of formation of the benzols has not been so thoroughly investigated as the subject deserves. In general, high temperatures favor the formation of compounds of the aromatic series such as benzene, toluene, xylene, etc., but these, in turn, undergo molecular condensations

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[*] Diplom. Arbeit, Aachen, 1905.

[†] *J. Gasbel.* 1886.

at still higher temperatures, forming naphthalene and anthracene, etc., so that there is a certain balance of conditions favoring the maximum formation of the benzols. Moderate coking temperatures favor the formation of toluene, which appears to be more easily decomposed than benzene.

Gas.—Considering now the gas, we find this composed principally of methane and hydrogen with smaller amounts of ethylene, carbon monoxide, carbon dioxide, hydrogen sulphide and nitrogen. The gas produced by low temperature distillation, like the corresponding tar, contains noteworthy amounts of higher members of the methane series such as ethane, propane, etc., and also larger amounts of ethylene, together with other olefines. These all undergo decomposition at higher temperatures, and methane itself is decomposed with the formation of complex aromatic hydrocarbons, free carbon, and hydrogen. Table XXI gives a composition of gas taken from a by-product coke oven at different intervals of time during carbonization.

Table XXI.—Composition of the Gas During Carbonization (Percent by Volume)

Hours coal carbonised.	CO_2	C_6H_6	C_2H_4	O_2	CO	CH_4	H_2	N_2	Minimum Calorific power (0°C. 760 mm.) calculated per cubic meter.
2	3.30	1.80	4.00	1:05	0.90	36.65	42.50	10.00	5,402
3	3.00	1.50	3.50	0.80	1.90	36.10	44.60	8.60	5,271
4	2.30	1.10	3.10	0 60	2.90	34.50	48.80	6.70	5,086
5	2.50	1.10	3.20	0.60	2.80	34.50	47.80	7.50	5,071
6	2.20	1.00	2.80	0.50	3.00	33.60	50.10	6.80	4,971
7	2.00	0.80	2.50	0.50	3.95	32.40	50.75	7.10	4,802
8	1.40	0.60	2.50	0.20	3.40	33.65	53.75	3.60	4,906
9	1.90	0.50	2.00	0.20	3.10	33.45	50.55	8.30	4,797
10	2.30	0.35	1.75	0.20	2.80	31.20	47.10	14.30	4,324
11	1.30	0.35	2.05	0.10	2.80	32.40	51.50	9.50	4,583
12	1.50	0.35	1.85	0.20	4.15	33.40	50.65	7.90	4,660
13	2.00	0.30	1.80	0.20	4.10	32.45	49.75	9.40	4,530
15	1.90	0.25	1.80	0.15	3.90	33.20	53.40	5.40	4,665
17	1.80	0.10	1.90	0.25	4.15	30.60	51.60	8.60	4,369
19	1.10	....	1.20	0.15	4.70	26.10	55.75	11.00	3,978
21	1.05	....	1.00	0.05	4.00	21.15	58.95	13.80	4,487
23	0.80	....	0.60	0.05	3.80	18.95	61.90	13.90	3,412
25	0.70	....	0.30	0.10	4.90	12.20	67.00	14.80	2,960
27	1.00	....	0.30	0.30	5.80	4.70	70.00	17.90	2,419
Heating gas	2.10	....	1.80	0.60	4.20	26.20	51.70	15.40	3,964

TABLE XXII.—TYPICAL ANALYSES OF GAS FROM KOPPERS BY-PRODUCT COKE OVENS

	CO_2	Illuminants	O_2	CO	H_2	CH_4	N_2	B.t.u.	Specific gravity
Straight gas before removing benzols........	2.2	3.5	0.3	6.8	47.3	33.9	6.0	591	0.44
Straight gas after removing benzols........	2.2	2.6	0.3	6.9	47.8	34.2	6.0	562	0.42
Rich gas before removing benzols...........	2.6	4.3	0.2	6.3	46.3	35.0	5.3	630	0.45
Rich gas after removing benzols...........	2.6	3.2	0.2	6.4	46.8	35.4	5.4	605	0.42
Lean gas before removing benzols...........	2.1	2.0	0.3	6.0	57.0	27.0	5.6	528	0.38
Lean gas after removing benzols...........	2.1	1.0	0.3	6.1	57.5	27.3	5.7	497	0.35

These analyses are taken from different plants, and consequently represent different coals and somewhat different operating conditions.

The gradual decrease of methane and increase of hydrogen is very noteworthy. The ethylene also decreases to a marked extent and the percentage of carbon monoxide remains practically stationary. Carbon monoxide appears to be produced from the decomposition of some of the oxygenated compounds in the coal and it is interesting that considerable variations in the percentage of hygroscopic moisture in the coal charge have little effect on the percentage of carbon monoxide in the gas; showing again how completely impervious the tar diaphragm is to the passage of the water vapor outward through the coke. The carbon dioxide is likely formed by low-temperature decomposition of some of the constituents of the coal inside of the coking area, and the amount gradually decreases as carbonization advances, because most of the carbon dioxide formed in the later stages of the process must be reduced to carbon monoxide. The oxygen comes from leakage in the gas mains and from the air originally present in the oven, and may be disregarded. Part of the nitrogen comes from leakage in the mains, but most of it is derived from leakages from the heating flues. The gaseous nitrogen actually derived from the coal itself would be extremely small in amount. Analyses of typical coke-oven gas from American by-product plants are given in Table XXII.

As has been described on page 170, advantage is often taken of the differences in character of the gas produced in the first half of the distillation period from the leaner gas produced in the last half, to separate the gas in such a way that the leaner gas containing a high percentage of hydrogen and a low percentage of methane, and having a low calorific value, may be used to heat the ovens, while the gas containing high percentages of methane and illuminating hydrocarbons may be sold for purposes that demand a high heating or illuminating value.

Reference should also be made in this connection to the investigations of H. C. Porter and F. K. Ovitz.[*] Table XXIII shows the total gas yield and composition at different temperatures taken from their experimental data. Ten grams of air dried coal were heated in a platinum crucible and the gas analyzed.

Table XXIII.—Coal No. 1 (Zeigler, Ill.)

Temperature of furnace (degrees Centigrade)	500	600	700	800	900	1,000	1,100
Highest temperature reached in coal	390	480	585	685	811	920	1,026
Gas at 25°C. (c.c.)	197	535	980	1,550	2,335	2,700	3,120
Composition of gas:							
CO_2	23.8	7.6	6.4	3.9	2.5	2.7	1.8
Illuminants	6.5	5.0	4.1	3.3	3.2	3.7	4.0
CO	16.5	16.1	21.1	16.9	15.2	15.1	16.1
CH_4, C_2H_6, etc.	49.5	55.0	41.5	34.4	27.8	23.1	19.4
H	3.7	16.3	26.9	41.5	51.3	55.4	58.7
Value of n in C_nH_{2n+2}	1.42	1.29	1.21	1.16	1.22	1.18	1.23
Coal No. 3 (Connellsville, Pa.)							
Highest temperature reached in coal, degrees Centigrade	390	474	589	705	812	922	1,010
Gas at 25°C. (c.c.)	161	718	1,220	1,723	2,080	2,900	3,530
Composition of gas:							
CO_2	15.9	4.2	3.2	2.0	1.1	1.2	1.0
Illuminants	9.1	7.1	4.3	4.5	4.8	4.6	5.2
CO	7.8	6.0	6.3	7.2	7.4	6.4	7.3
CH_4, C_2H_6, etc.	63.3	64.4	55.8	47.0	33.2	29.0	26.3
H	3.9	18.3	30.4	39.3	53.5	58.8	60.2
Value of $_n$ in C_nH_{2n+2}	1.69	1.37	1.27	1.21	1.22	1.11	1.15

The foregoing data also show the rate of increase of the *total yield* of gas produced with increasing temperatures. Some of the conditions of the formation of ammonia have already been

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[*] U. S. Bureau of Mines, *Bull.* 1.

discussed on page 110. Only a comparatively small amount of the total nitrogen in the coal is actually converted into ammonia in the coking process, and the ammonia actually formed undergoes partial secondary decomposition, forming nitrogen and hydrocyanic acid, such decompositions increasing markedly above 850°C. and being promoted by the presence of certain catalytic agents such as oxide of iron. The plan of disposing of blast-furnace flue dust by incorporating it with the coal previous to carbonization has been a failure on account of the great decrease in the yield of ammonia produced from the mixture.

Ammonia and Cyanogen.—Simmersbach[34] made a very complete series of laboratory experiments on the formation of ammonia and cyanogen during the distillation of coal and on the decomposition of ammonia in the presence of incandescent coke. His conclusions are as follows:

1. The formation of ammonia occurs mainly at a temperature at which the coking of coal is already terminated.
2. The formation of ammonia does not attain its maximum at one and the same temperature for all coals.
3. This temperature depends upon the nature of the nitrogen compounds in the coal and varies from 800 to 900°C.
4. Decomposition of ammonia (which with concentrated ammonia occurs essentially at 750°C and nearly completely at 800°C.) is, owing to the attendant dilution, not in evidence during the gasification of coal until 900°C., is reached, and it increases with the increasing temperature.
5. The formation of cyanogen increases with the quantity of ammonia and with increasing temperature although ammonia in concentrated form has an unfavorable influence upon the formation of cyanogen with increasing temperature above 900°C.
6. The quantity of cyanogen formed during coal carbonization amounts to about 1.2 per cent of the total nitrogen and to about 5 per cent of the ammonia.
7. Water vapors are detrimental to the formation of cyanogen, but favorable to the ammonia yield.
8. Higher gas velocity checks the decomposition of ammonia.
9. The size of grain of the coal has no influence on the temperature of maximum ammonia or upon the yield itself.

PROCESSES AND APPARATUS FOR THE RECOVERY OF BY-PRODUCTS FROM COAL GAS

Not only is ammonia relatively the most valuable by-product of coal, but if it were not extracted from the gas, the quality of the latter would be injured for domestic purposes, although it might be used for industrial heating. The extraction of the tar is necessary for the recovery of the ammonia and for the satisfactory handling of the gas.

Extraction of benzols is not a technical necessity but a matter of commercial policy. The cost of recovery and the heating and illuminating value of the benzols in the gas must be balanced against the value of the commercial light oil products recoverable.

The market for cyanide compounds is comparatively limited, and the present inducements for the recovery of these materials are small. Enough of the hydrocyanic acid originally present in the raw gas is removed by the various processes involved in the recovery of the other by-products and in the final purification, so that this material does not impair the value of the gas.

Recovery of Ammonia and Tar.—In the older by-product coke and gas plants, ammonia was always recovered by scrubbing the gas (after the extraction of tar) with water, forming a weak-ammonia liquor, which was distilled to manufacture concentrated liquor, aqua ammonia, ammonium sulphate, and other compounds of ammonia. With the increasing demand for ammonium sulphate on the part of fertilizer manufacturers, it was found that the bulk of the ammonia recovered would have to be sold in this form, and efforts were made to manufacture ammonium sulphate directly by passing the gas through sulphuric acid, avoiding the intermediate steps of water scrubbing and distillation. These efforts developed several processes known as "direct processes" in contradistinction to the old "indirect process." However, for the manufacture of concentrated liquor, aqua, and compounds of ammonia other than the sulphate, the indirect process is still extensively used, although considerable amounts of these materials are derived from the ammonia liquor condensates obtained in some of the direct processes.

The only processes used extensively in America are the indirect process and the Koppers type of direct process. The Semet-Solvay Company has recently introduced another type of direct process.

The Indirect Process.—The gas leaving the coke oven battery at a temperature of about 150°C. passes into primary coolers where it is brought to a temperature of 15 to 20°C. In the usual type of primary cooler, the gas flows around numerous rows of vertical water tubes in a series of seven vertical passes. The water flows through the tubes in the same number of passes, but in a direction opposite to the flow of gas. Temperature regulators are usually provided to control the water-supply valves so as to maintain a constant outlet temperature.

The exhausters which handle the gas are next in order after the coolers. Either the positive type (*e.g.* Roots or Connersville) or turbo-exhausters (*e.g.* General Electric or Southwark) are used, the former having the advantage of a wider range of efficiency and the latter the advantage of compactness.

From the exhausters, the gas is sometimes passed through secondary coolers in order to take out the heat of compression. In recent installations, however, it is the practice to pass the gas directly into the tar extractors. The P. and A. (Pelouze and Audouin) type of tar extractor is usually employed.

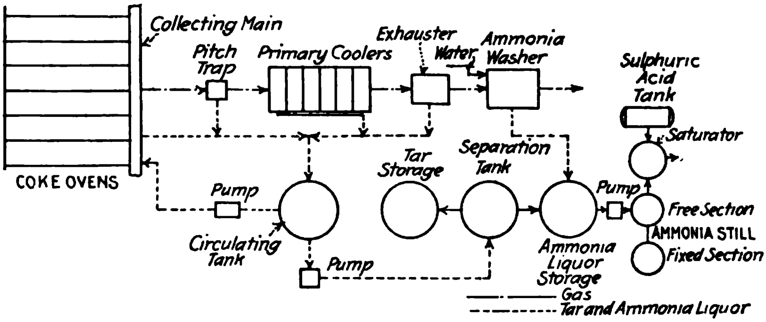

FIG. 46.—Indirect process for the recovery of sulphate of ammonia.

The clean gas from the tar extractor passes into the ammonia washer. Many gas works employ mechanically operated rotary washers; but the majority of by-product coke plants using the indirect process employ stationary bell washers. These are composed of trays, built one above the other, containing bells with serrated edges dipping into the liquor passing down through the washer. The gas passes upward into the bells in each tray, bubbling through the liquor. Water is put into the top of the washer and, as it meets the gas, dissolves out the ammonia to form the liquor which passes out at the bottom, where it usually contains about 1 per cent NH_3.

Figure 47 shows the exhausters, tar extractors, and ammonia washers in the plant of the LaClede Gas Light Co., at St. Louis, Mo. Here three ammonia scrubbers of the bell type are in use, each composed of 20 cast-iron sections, built up one above the other, 18 of which are active. Each section is divided, with respect to the washing liquid, into six long compartments having two bells and an overflow, the overflow on alternate corresponding compartments placed at opposite ends and at such a height that the high point of the serrations on the bottom of the bells are immersed ½ in. in water when sealed and ready for use. A large overhead tank in two compartments provides for the use of either fresh or very weak ammoniacal liquor for scrubbing at a constant head, and the compartments of the top section are provided with individual sight feed glasses for aid in adjusting the water supply, which flows from the top down. Gas enters the bottom of the scrubber and is made to bubble upward through the seals; the ammonia in the gas is gradually but fully absorbed by the descending water, which increases in ammonia strength on its way down and drains away at the bottom through a seal to a small reservoir. The advantages of scrubbers of this type are as follows: There are no moving mechanical parts; the scrubbers are easily cleaned and inspected; the wear and tear is practically nil, as the parts are all cast iron and only subjected to weak ammonia water.

FIG. 47.—Gas washers, tar extractors and exhausters for indirect process installed by The Koppers Company for the Laclede Gas Light Company, St. Louis, Mo.

We have now to consider the ammonia and tar condensates derived from the system preceding the ammonia washers. A large amount of tar is condensed in the collecting main and in the "off-take mains" connecting this with the primary coolers.

Additional tar, together with a large amount of ammonia liquor derived from the moisture in the coal, comes out of the gas in the primary coolers. The rest of the tar is taken out in the tar extractors. All of these condensates flow into a large tank called the circulating tank, from which a portion is continually pumped over the collecting and off-take mains, while the excess is pumped into a tall separating tank. Here the tar and liquor, by reason of the difference in their specific gravities, separate in two layers, and are automatically drained into the tar storage tanks and the liquor-storage tanks respectively. The liquor from the ammonia washers is pumped directly into the liquor storage tanks.

FIG. 48.—Ammonia stills.

The tar storage tanks are provided with steam heating coils to facilitate the separation of additional liquor which is returned to the liquor tanks. The tar is readily dried to a content of less than 2 per cent. liquor and is then ready for shipment.

For the manufacture of ammonium sulphate, the liquor is distilled in a continuous column still consisting of four essential parts, *viz.*, the free still, the fixed still, the lime leg, and the dephlegmator or water separator. The free and fixed stills are exactly alike in construction, but may differ in the number of trays. The trays are similar in principle to those of the ammonia washer. The liquor is fed from an overhead storage tank into the top tray of the free still. It passes down through this still where it is deprived of its ammonia by the steam and vapors that bubble up through the bells. Thence it passes into the lime leg, where it is mixed with sufficient milk of lime to decompose all of the fixed ammonium compounds (principally the chloride). The mixture goes into the fixed still and passes down through the trays where the rest of the ammonia is expelled. The waste liquor, consisting principally of lime compounds dissolved or suspended in water, goes to the sewer.

Steam is put into the bottom of the still and follows a course opposite to that of the liquor, carrying with it the ammonia along with carbon dioxide, hydrogen sulphide, hydrocyanic acid and other gaseous impurities. The mixture of steam, ammonia, and gases passes into the dephlegmator or water separator, where any condensate is collected and returned to the still; thence into a saturator.

The saturator commonly used is a large steel-jacketed, lead-lined vessel, with the following auxiliaries:

1. The cracker pipe.
2. The ejector.
3. The drain table.
4. The lye pot.
5. Centrifugal driers.

The saturator, under normal conditions of operation, contains a saturated solution of ammonium sulphate holding some ammonium sulphate crystals in suspension and containing about 50 grams per liter of sulphuric acid, which strength is maintained by the continual flow of a stream of sulphuric acid into the lye pot. The vapors enter the saturator through a lead-covered pipe which communicates with the cracker pipe lying underneath the level of the liquid. The cracker pipe has perforations or serrated edges which bring the gas into intimate contact with the liquor. The reaction between the ammonia and the sulphuric acid is extremely rapid and the heat of the reaction is sufficiently great not only to prevent condensation of water, but actually to evaporate any water going into the saturator with the sulphuric acid or with necessary washings. The waste gases escape through a vent pipe which often carries a trapped condenser to prevent any condensate refluxing into the saturator. These vapors are of an extremely noxious character and various means usually have to be devised to get rid of them so as to prevent a nuisance. They are often led to the stack of the oven or boilers. The condensate, on account of its offensive smell, has earned the name of "devil liquor." It is difficult to deal with. It is sometimes mixed with the still waste, sometimes run into the soil and often filtered through spent oxide from the gas purifiers.

As the reaction in the saturator proceeds, solid ammonium sulphate accumulates and must be removed. In the older types of saturators, the front of the saturator was open and was separated from the gas chamber by a sealed baffle under which the sulphate crystals could be raked out by hand. On modern plants, the closed type of saturator is used. The ejector extends to the bottom of the saturator and, operated by steam or compressed air, forces the mother liquor and crystals out over the drain table. Here the crystals accumulate while the mother liquor returns through the lye pot into the saturator. When sufficient sulphate has accumulated on the drain table, the ejector is temporarily shut off and a trough is lowered connecting the outlet of the drain table with the basket of one of the centrifugal driers. The basket is lined with perforated copper sheeting which effectively resists the action of the acid. The capacity is commonly about 500 lb. per load. The sludge, consisting of ammonium sulphate crystals mixed with the mother liquor, is raked into the drier, the trough is raised and the operation of the ejector is resumed. The drier is spun for about 8 min. during which time the crystals are washed with a little fresh water. The adherent mother liquor and the washings run back into the saturator through the lye pot. After spinning the drier is stopped, the bottom cover raised, and the ammonium sulphate scraped down into a handbarrow or into a bin communicating with an elevator. By this process, ammonium sulphate is produced containing 25 per cent NH_3 and from 0.4 to 0.5 per cent free H_2SO_4.

The operation of the saturator is practically continuous.

The principal condition to be regulated is the percentage of excess acid in the bath. The operator takes samples of the mother liquor at frequent intervals, determines the excess acid by titration and regulates the flow of the acid accordingly. Commercial sulphuric acid of 60° Bé is usually employed.

Direct Process.—Where the bulk of the ammonia is to be recovered in the form of sulphate, it is desirable to produce this material by passing the gases containing the ammonia directly into the sulphuric acid. Obviously it is necessary to remove all tarry matter before this can be done.

The simplest method would naturally be to extract the tar from the hot gases, directly after leaving the ovens, at such a temperature that all of the ammonia compounds would remain in a gaseous form, and then to pass the gases directly through saturators. This is the principle of the Otto and Simon-Carves direct processes that have found application in European plants, but are not used in America.

The chief drawbacks to this simple scheme are due to the difficulty of thoroughly cleaning the gas at the high temperatures necessary and to the presence of ammonium chloride which is the chief constituent of the fixed salts of ammonium present. Another disadvantage is due to the large amount of naphthalene carried forward by the hot gases. This naphthalene must be gotten rid of by oil-operated naphthalene washers or by cooling and scrubbing with water after the gases have passed through the saturators.

The difficulty due to ammonium chloride is the most important and may cause much annoyance and expense. If temperature conditions are not carefully regulated, much of the ammonium chloride will condense along with the tar from which it must be removed by washing and distillation. If this is done, the process assumes the same character as those in which direct cooling of the gases is practiced. If part or all of the ammonium chloride is made to go with the gas into the saturators, it is decomposed by the sulphuric acid forming hydrochloric acid. This powerfully corrosive acid escapes with the gas from the saturators and quickly ruins any steel piping that may be used. The only way to overcome this trouble is to wash the hydrochloric acid out of the gas in a special apparatus which, together with the connecting piping, must be made of acid-proof material. This involves a considerable increase in the cost and maintenance of the plant.

Although the Otto and Simon-Carves processes were originally designed to clean the gas at a sufficiently high temperature to retain the ammonium chloride, both have surrendered to the difficulties resulting from the presence of this substance.

The Otto process uses a hot tar spray to clean the gas, but sufficient liquor is used with the tar to absorb all the ammonium chloride. The Simon-Carves process uses a centrifugal separator of the cyclone type, followed by a rotary tar extractor for cleaning the gas. Sufficient water is used to remove the ammonium chloride. The ammonium chloride solution may be evaporated and produce an impure salt, but is frequently distilled, the vapors being put into the gas before it enters the saturators.

At the same time that the direct processes of this type were being developed, H. Koppers, realizing their inherent disadvantages, devised a process that has found wide application with entirely satisfactory results. In this process the gases from the ovens are cooled, and passed through tar extractors exactly as in the indirect process. The cool, clean gases are then reheated to a temperature of about 65°C. and passed through the saturators. The ammonia liquor from the condensing system is separated from the tar by the system of tanks used in the indirect process and is then distilled, the vapors passing into the gases as they enter the saturators. The essential feature in the Koppers process as it is now practiced, consists in the use of the reheater, which makes it possible to adjust the temperature of the gases entering the saturators so that proper conditions of equilibrium are maintained irrespective of variations of the amount of water entering the saturators.

The Coppée process used in Europe aims to dispense with the reheater by reducing the amount of moisture entering the saturators. The vapors from the still are carried through a drier which returns excess moisture back through the still, thence the vapors proceed to the gases entering the saturators.

In the Still process, the gases from the ovens are cooled by means of cold ammonia liquor. The liquor itself becomes heated to about 90°C. and is separated from the tar and sprayed into the cooled gas. This raises the temperature of the gas to about 80°C. while the liquor is again cooled to about 25°C. Any free ammonia is taken up by the gases which then enter the saturator. In order to prevent the liquor from gradually becoming hotter in this process of circulation, an intermediate cooler is used in which the gas temperature is controlled by external water circulation. Ammonium chloride and other fixed salts accumulate in the liquor and may be recovered by evaporation.

The Semet-Solvay Direct Process.—A direct process developed by the Semet-Solvay Company is described in U. S. Patent No. 1163752, granted to August F. Hilleke. Figure 49 shows the arrangement of apparatus used in this process. The gas as it comes from the ovens in the main, *A*, is first scrubbed in a wash tower, *B*, with the water of condensation from the gas. In this operation, the gas is cooled to a temperature of from 30 to 45°C. The fixed ammonia compounds with more or less free ammonia go into solution in the condensed water. The effluent from the scrubber, *B*, consisting of tar and ammonia liquor passes into a tank, *C*. In order to maintain the cooling of the gas, a portion of the liquor is conveyed by the pump, *N*, through cooling coils, *D*, to the top of the scrubber, *B*, where it is again used for scrubbing the gas.

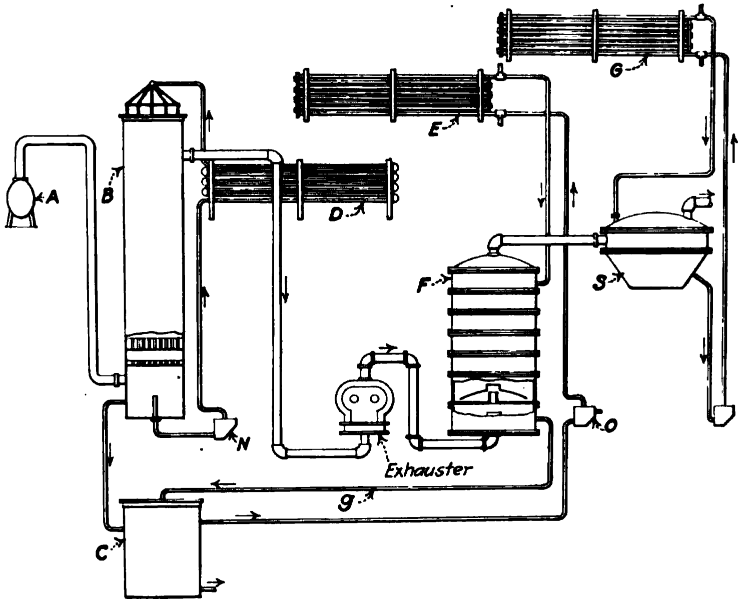

FIG. 49.—Hilleke direct process (Semet-Solvay) for the production of sulphate of ammonia.

It is claimed that the temperature attained by the gas in the scrubber, *B*, will not affect the ultimate result. The higher the temperature of the gas, the less cooling of the wash water will be required. The lower the temperature of the gas, the more complete will be the removal of the tar at this point and the less power will be required to convey the gas through the apparatus.

After leaving the scrubber, *B*, the gas is heated to its initial saturation temperature and brought in contact with the water of condensation. This operation is effected by passing the water of condensation from the tank, *C*, by means of a pump, *O*, through the heating coils, *E*, where it is subjected to steam heat and from which it passes into the top of a wash column, *F*. The gas enters at the bottom of the wash column, *F*, and bubbles up through the hot water therein. The temperature of the gas is thus raised to, or even above, that of the gas as it enters the scrubber, *B*, and the water of condensation together with all its contained free ammonia is again taken up by the gas. Any tar remaining in the gas is removed by the passage of the gas through the water at this point and, together with the unvaporized water, flows back to the tank, *C*, through the pipe, *G*.

It is stated that a balance of operation is effected, whereby the tar and fixed ammonia are removed from the gas; and the entire amount of free ammonia is returned to the gas. From the wash tower, *F*, the gas passes to a saturator, *S*, to form ammonium sulphate. In case of undue accumulation of liquor in the saturator, *S*, with consequent dilution of the acid, the liquor may be again returned to the gas by being pumped through the heating coils, *G*.

It is evident that a concentration of the fixed ammonia salts takes place in the liquor circulation system before the saturator. A portion of the liquor is drawn off from the tank, *C*, from time to time and subsequently treated as desired for the recovery of the contained salts.

Obviously, this operation as described is similar in principle to the Still process. The water of condensation is, however, cooled indirectly with cold water and not by the gas. The heating of the water of condensation is also effected by external means. The essential advantages claimed for the process are as follows:

1. The cooling and heating of the water of condensation by which the cooling and heating of the gas is effected is not dependent in any way on the gas temperature.
2. No indirect heating or cooling of the gas is required and no critical

observation of the temperature of the gas is called for since the only absolute temperature necessary is that the gas shall be raised to its original saturation temperature.

The Koppers Direct Process.—This is used by the majority of modern American by-product coke plants. The hot gases from the ovens are drawn through the off-take mains to the primary coolers and thence pass through the exhausters and *P* and *A* tar extractors just as in the indirect process. Condensates of tar and liquor from this apparatus are collected in the circulating tank, but the circulating system for the collecting and off-take mains is arranged so that tar is used as the cooling medium instead of liquor, contrary to the practice in the indirect process.

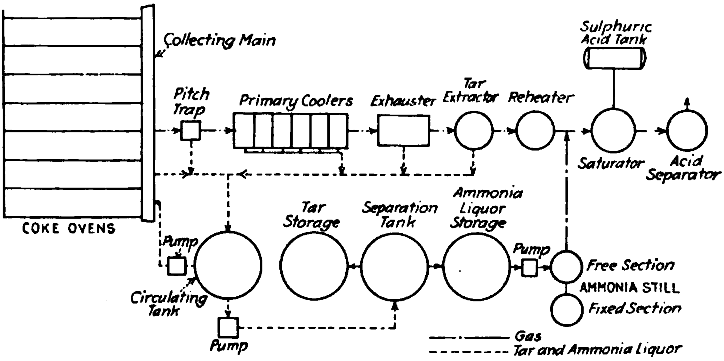

FIG. 50.—Koppers direct process for recovery of sulphate of ammonia.

From the tar extractors, the gas passes through reheaters which are steel tanks containing steam pipes around which the gas is caused to circulate. The gas from the reheaters enters the saturators at a temperature of about 65°C. The saturators are similar in construction to those used in the indirect process, but are of course very much larger on account of the great volume of gases that must be handled. Above each saturator is an apparatus called the "acid separator" through which the gas from the saturator passes. The acid saturators are lead lined and baffled so as to remove any spray of mother liquor and sulphate that the gas may carry.

The ammonium sulphate formed in the saturators is handled by means of ejectors, drain tables, and centrifugal driers exactly as in the indirect process. The crystals are larger and easier to wash and dry than in the indirect process and the product has a higher degree of purity, especially with respect to low free-acid content.

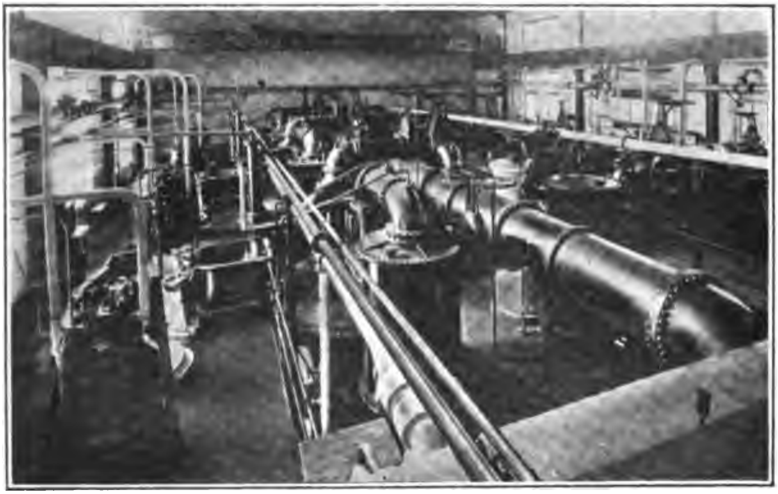

Fig. 51.—Interior by-product building, Koppers direct process.

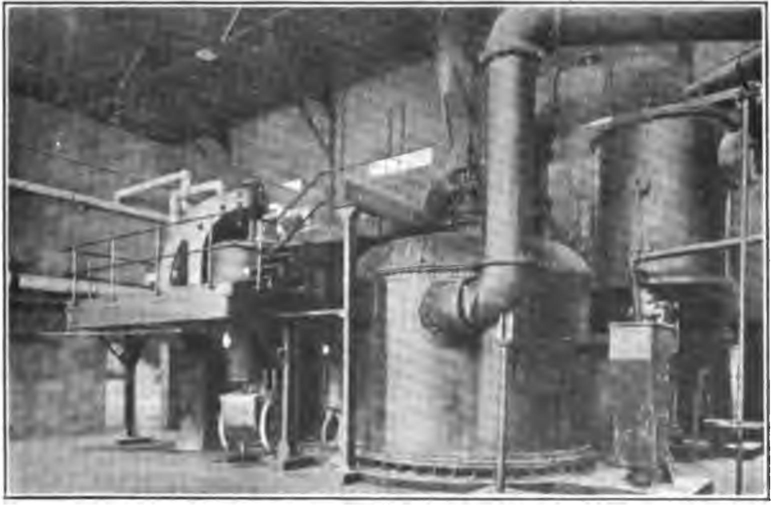

Fig. 52.—Saturator, acid separator and centrifugal dryer, Koppers direct process.

The tar and liquor from the circulating tank is pumped to a separating tank from which the tar goes to tar storage tanks while the ammonia liquor goes to a separate tank. From this, it is pumped to a still where it is treated exactly as described in the indirect process except that the vapors pass into the gas entering the saturators. The ammonia thus distilled amounts, as a rule, to 25 per cent. of the total ammonia produced from the coal. The following advantages are claimed for the Koppers direct process:

1. The indirect process requires a large plant for the distillation of ammonia liquor. The direct process needs a comparatively small still capacity which is part of the main plant. Thus, less labor and supervision are required.
2. There is less opportunity for loss of ammonia in the various operations and the efficiency of recovery is higher.
3. The efficiency of recovery is independent of water temperature. An adequate supply of cold water is essential for the efficient recovery of ammonia by the indirect process; but the direct process has no such requirement.
4. No water is required for scrubbing.
5. Less pumping capacity is required.
6. Much less steam is required for distillation. The only effluent to be disposed of is the water condensed from what is driven out of the coal with some added condensate from the steam.
7. The saturators have a longer life than those used in the indirect process since they are operated at lower temperatures.
8. The deposition of naphthalene in pipes, washers, etc., is minimized.
9. The cost of installation is less than for the indirect process.

MANUFACTURE OF CONCENTRATED AMMONIA LIQUOR

Where it is desired to convert all of the ammonia into concentrated liquor, the indirect process must be used. With the Koppers process, about 25 per cent of the ammonia may be worked up as concentrated liquor by adding to the ammonia stills the necessary concentrating and purifying apparatus.

Where crude concentrated liquor is to be manufactured without regard to the amount of ammonium sulphate or carbonate that it may contain, the still is equipped simply with a dephlegmator by which the strength of the condensate is regulated usually to about 18 per cent. NH_3. The vapors from the dephlegmator pass into a water cooled condenser and the condensed liquor goes directly to steel storage tanks.

Where it is desired to eliminate more or less carbon dioxide and hydrogen sulphide, this is accomplished by heating the weak liquor to about 90°C. at which most of the H_2S and CO_2 escape, carrying with them a minimum amount of ammonia.

The escaping gases are washed with a little water in order to prevent the loss of ammonia and the liquor thus formed is put back into weak liquor entering the separator. From the separator, the liquor is distilled and the vapors dephlegmated and condensed in the usual manner. Various combinations of heat exchangers, using the heat in the still waste and in the vapors for pre-heating the incoming weak liquor, find application in different systems.

The manufacture of aqua ammonia requires still more complicated apparatus in which the vapors, partially freed from CO_2 and H_2S, pass through lime washers, caustic washers, oil washers and animal charcoal, in order to complete the removal of carbon dioxide, hydrogen sulphide, pyridine and other organic impurities. The purified vapors are absorbed in distilled water.

RECOVERY OF BENZOLS

Coke-oven gas leaving the ammonia recovery apparatus contains certain non-aqueous, condensible vapors that have not been affected to any important degree by the previous operations. These vapors are for the most part made up of substances of the benzene series—principally benzene, toluene, and xylene—and are generically called benzols.* Of the total light oil recovered from the carbonization of the coal, 95 per cent results from scrubbing the gas, and only 5 per cent is found in the tar.

The following table shows the composition of a typical coke-oven light oil with respect to the most important constituents:†

	Per Cent in Light Oil	Gallons per Ton Coal
Pure benzol	52	2.08
Pure toluol	14	0.56
Xylols	8	0.32
Solvent naphtha	10	0.40
Other substances (principally hydrocarbons)	16	0.64

Such a light oil would be produced in the proportion of about 4 gal. per ton of coal, and approximately 70 per cent. of it or 2.8 gal. per ton of coal would be produced as motor fuel.

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* Following the usual technical practice in this country, the termination "ol" is used for commercial products and the termination "ene" is used for the chemically pure substances. Thus by "pure benzol" we mean material coming up to the regular commercial standard of purity.

† For laboratory methods used in benzol-recovery plant operation, see Hamor and Padgett's, "The Examination of Petroleum," **1920**, 199–241.

Exclusive of water, the light oil vapors remaining in ordinary coke oven gas after the usual process of condensation and ammonia recovery, amount to about 1 per cent. by volume of the gas. They might be removed by cooling the gas to a very low temperature and this was actually done on a large scale in Europe some years ago, but the method was handicapped by mechanical difficulties largely due to the separation of ice and has been altogether abandoned. The only practical alternative which can be employed to recover these vapors, without altering their chemical constitution, is to treat the gas with a medium in which the vapors are soluble and from which they may be recovered by simple distillation.

This is the principle of every benzol recovery process in operation at the present time. It appears to have been first employed in 1859 by Vogel who washed coal gas with fatty oils for recovering the benzol. Various processes for extracting benzol based on this principle were later patented; but it was not until 1887 that it was put into successful commercial operation. This was done in Germany by F. Brunk, who is generally acknowledged as being the founder of the modern benzol-recovery industry.

In America the wash oil generally used to absorb the benzol is a petroleum product usually known as straw oil, of which at least 90 per cent should distil between 250 and 350°C. A good absorbent oil has a specific gravity of less than 0.88 at 15°C. and is readily fluid at 4°C. It should not emulsify with water. In best practice the amount of benzol absorbed (technically the "enrichment") is kept between 2 and 3 per cent of the absorbing oil. Too high enrichment is likely to lead to loss of benzol and too low enrichment may involve needless consumption of absorbing oil and steam. In European practice heavy tar oils are used almost exclusively as absorbing media and such materials may find increasing application in America. Such tar oils should contain less than 7 per cent naphthalene and 90 per cent of the material should distil between 200 and 300°C.

The various systems of benzol recovery are similar in principle and differ only with respect to details of construction and arrangement of apparatus. The Koppers system may be taken as an example of the most complete of the modern systems especially with relation to its patented arrangement of heat exchangers.

Light Oil Recovery.—Figure 53 shows a flow sheet of a benzol plant with its principal features of operation. Let us first follow the course of the gas and then that of the oil. Previous to treatment with the absorbing oil, the gas should be cooled to a suitable temperature, commonly about 25°C., though this may vary from plant to plant and depends principally upon such factors as the moisture and naphthalene content of the gas, temperature of the wash oil, and percentage of enrichment desired. This cooling is accomplished by means of the cooler (A), which is preferably of the direct contact type. The water acts not only as a cooling medium, but mechanically washes a large portion of the naph-

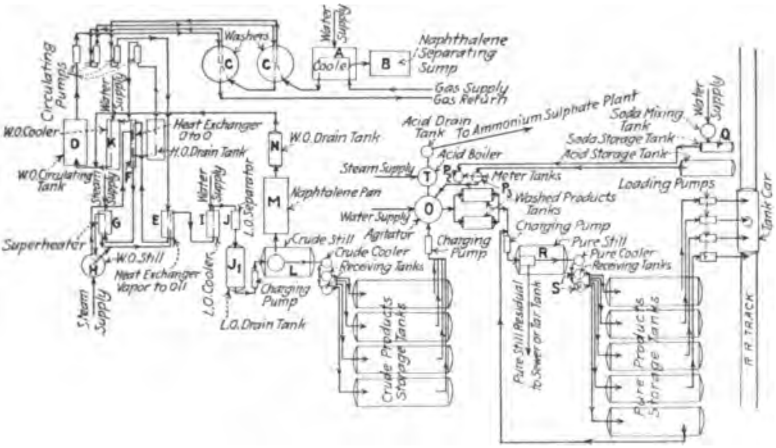

FIG. 53.—Flow-sheet of benzol plant.

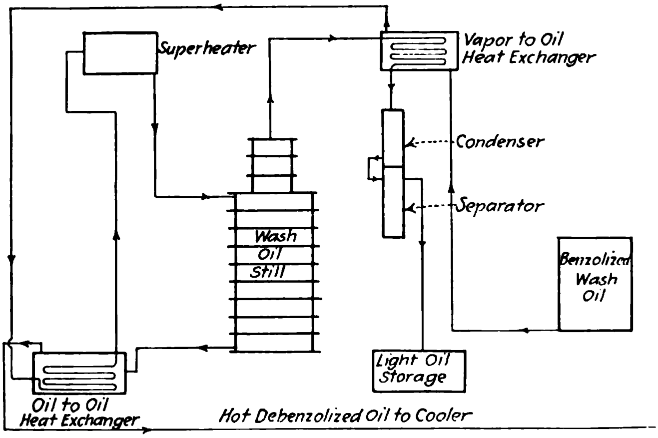

FIG. 54.—Arrangement of heat exchangers in Koppers benzol recovery system.

thalene out of the gas and carries it into the separating sump (*B*). The cool gas then passes into the benzol washers (*C*). These are tall scrubbing towers of the hurdle type, effecting a very intimate and prolonged contact between gas and oil. The debenzolized gas passes out of the last washer through the return main to its point of consumption.

The fresh wash oil is pumped from the circulating tank (*D*) over the scrubbers in an opposite direction to the flow of the gas, bringing the fresh washing medium into the scrubbing system at a point where the gas contains the least light oil vapors. The distribution of the wash oil over the tops of the scrubbers is a very important matter, and should be done as uniformly as possible. The enriched wash oil accumulates in tanks usually located underneath the scrubbers, and is pumped from these to the benzol recovery plant to be heated for the purpose of releasing its benzol constituents. Part of this heating is accomplished by the utilization of the heat in the hot debenzolized wash oil leaving the still. Two heat economizers are used in the Koppers system. The cold oil first enters the heat exchanger (*E*), where it is heated by benzol vapors and steam from the still (*H*), thence it is con-

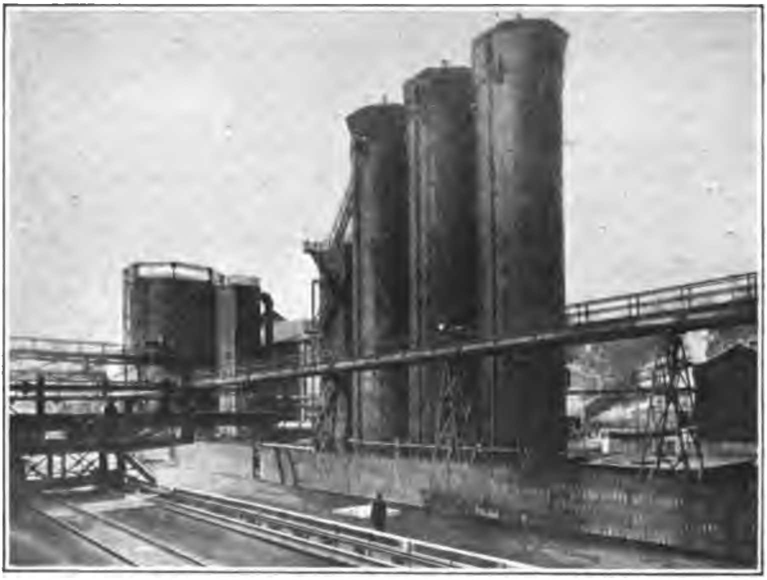

FIG. 55.—Benzol scrubbers, Koppers system, McKinney Steel Company, Cleveland, Ohio.

ducted to a second heat exchanger (*F*), where it receives additional heating by means of hot debenzolized wash oil leaving the still (*H*). It is then still further heated to the maximum temperature desired by means of live steam in a superheater (*G*), from which it passes into still (*H*). This still is composed of a series of superimposed sections or chambers as in common distillation practice. The heated oil flows down through these sections while steam is blown directly into the lowest section and travels in a direction opposite to that of the oil. The upper portion of the still is arranged to act as a separator, removing any wash oil mechanically carried by the mixture of steam and benzol vapors. The vapors then enter the heat exchanger (*E*), as mentioned before, where they are partly condensed and the partial preheating of the enriched wash oil is effected. The remaining vapors are completely condensed and the total condensate cooled in a water-cooled condenser (*I*). The light oil is separated from the water in the condensate by means of the separator (*J*).

The debenzolized wash oil after leaving the still passes through the heat exchanger (*F*), where it gives up a part of its heat to the enriched wash oil, as stated above. Then it is finally cooled in the water cooler (*K*). The cool oil is next delivered to circulating tank (*D*), thus completing the cycle. The arrangement of heat exchangers in the Koppers system is shown in elevation in Figure 54.

Crude Fractionation.—The light oil is accumulated in a drain tank (*J*) shown in the lower part of the figure, and portions are taken for distillation in still (*L*). This still is usually known as the crude still, the first distillation of the wash oil being made for the purpose of effecting an approximate separation of several fractions of different boiling points preliminary to washing and final rectification. This and subsequent distillations are made intermittently in stills of large capacity (5,000 to 12,000 gal.). The method of distilling the light oil depends upon the final products that are desired, and the number of distilled fractions may be from one to three or four. In distilling to make motor fuel, one distilled fraction is usually all that is necessary. The heating is accomplished by means of internal steam coils and a direct steam spray. The benzol and toluol are principally distilled off by indirect heat, using the steam coils, and the higher boiling constituents, xylol, solvent naptha, etc., are then distilled over by introducing steam directly into the still.

After the completion of the distillation, a certain amount of wash oil containing naphthalene remains in the still tank, The presence of wash oil in the light oil is due not only to mechanical trapping of the heavy oil during the distillation, but also to the actual distillation of some of its original constituents by agency of the direct steam used.

The wash oil remaining in the still is drained into cooling pan (*M*), where it is cooled in the air to crystallize out the naphthalene. The wash oil is drained away from the latter into tank (*N*), and then may be returned to the main circulating tank (*D*). In large plants where the amount of naphthalene is great, a centrifugal dryer is employed for the purpose of separating the small amount of oil remaining in the naphthalene, and also for reclaiming the naphthalene from the separating sump at the foot of the gas cooler. The crude naphthalene so obtained can be sold as such, or may be put into the tar in the coke plant.

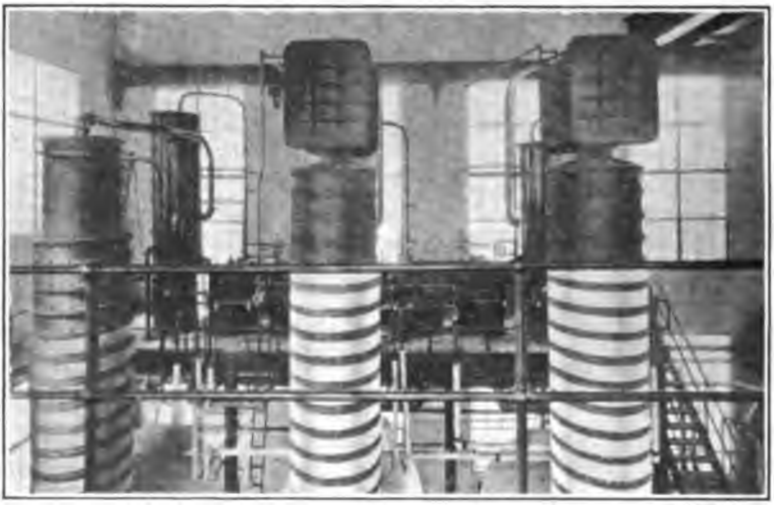

Fig. 56.—Benzol stills, Koppers system, Colorado Fuel and Iron Company, Pueblo, Colo.

Washing and Rectification.—The products obtained from the crude still will satisfy many commercial purposes in normal times. However, at present the demands of chemical manufacturers for benzol and toluol of a high degree of purity have made it advisable to accomplish the complete process of purification at the coke plant to serve this important part of the trade. For this purification the crude benzols are first washed with sulphuric acid and then with caustic soda and water. This operation is accomplished in agitator (*O*), which is a large lead lined vessel with an efficient mechanical mixing device for bringing the acid and benzol into intimate contact. The acid is commercial concentrated sulphuric acid (66°Bé.). The quantity used is accurately measured from the meter tank (p_3). The caustic soda solution is prepared in the tank (*Q*) and measured in the meter tank (p_2).

The acid has the effect of reacting with and to a large extent polymerizing most of the impurities which consist of various olefines and substances of similar character, together with certain phenoloid bodies. The action results in the formation of resinous substances of very high boiling point, part of which are insoluble in the benzols and settle out with the acid in the bottom of the agitator, while part go into solution, giving the benzol a dark brown or reddish color. The acid sludge is drawn off and treated as will be described later. The caustic soda neutralizes any traces of acid which may remain in the agitator and effects the removal of some of the phenoloid bodies. The washed benzol is delivered from the agitator to the still (*R*). This still is generally of the same capacity as the crude still, but is provided with a very efficient dephlegmator.

The operation of this "pure still" depends upon whether it is desired to make pure benzol and toluol or motor fuel. The distillation of motor fuel is very simple and rapid, while the production of pure products must be conducted with more care, laboratory tests being made frequently to check the quality of the distillate.

The water and caustic soda used in the agitator are drained to the sewer. The acid sludge drained from the agitator is delivered to a boiler (*T*), in which it is treated with direct steam. This effects a separation of the resinous materials in the form of a heavy carbonaceous, spongy deposit. An acid of about 40°Bé. is recovered and may be used on the coke plant for making ammonium sulphate. The boiler is covered during the operation of steaming and the escaping vapors are condensed in a cooler.

Regarding other details such as the arrangement of pumps, storage tanks and piping, the diagram is self-explanatory.

The decision to install a benzol recovery plant depends upon the commercial value of the benzol products as related to the cost of recovery and to the quality of gas required. Even if sold as motor fuel, the value of the benzol extracted is greater than its fuel value if left in the gas; and in the case of a by-product coke plant operating in connection with a blast furnace or steel plant, and sending its gas to the latter, the recovery of benzol will always be profitable. On the other hand, in the case of a by-product coke plant built primarily to supply gas for domestic purposes, such gas must necessarily command a higher value, and the profit obtainable from the recovery of benzol must be balanced against its value in the gas. This is especially true when the gas is sold on a heat unit basis, and in many cases under normal conditions it hardly pays to recover benzol from the gas sold.

The loss in heating value due to scrubbing out the light oil in practical operation is found by J. W. Shaeffer* to be 5.8 per cent of the original heating value of the gas. This was computed from the average of results obtained by a large number of American by-product coke plants.

According to Shaeffer, the heating value of the gas after the scrubbers may be calculated as follows:

$$\text{B.t.u. per cubic foot of scrubbed gas} = \frac{a - 121,827b}{1 - 35b}$$

Where a = The B.t.u. per cubic foot of the gas before scrubbing.
b = The gallons of light oil removed per cubic foot of gas.
35 = The cubic feet of vapor per gallon of light oil.

The constant 121,827 is the product of 17,567, the B.t.u. per pound of light oil; 7.3, the pounds per gallon of light oil, and 0.95, a correction factor correcting for the amount of absorbing oil in the light oil. The amount of absorbing oil is assumed to be 5 per cent.

THE TESTING OF COKE

The determinations required in the testing of coke for ordinary purposes are as follows:

1. Proximate analysis:
    (a) Moisture.
    (b) Volatile matter.
    (c) Ash.
    (d) Fixed carbon.
    (e) Sulphur.
    (f) Phosphorus.

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* *Proc. Am. Gas Inst.*, **11** (1916), 514.

2. Ultimate analysis:
    - (*a*) Carbon.
    - (*b*) Hydrogen.
    - (*c*) Oxygen.
    - (*d*) Nitrogen.
    - (*e*) Sulphur.
3. Analysis of ash.
4. Fusing point of ash.
5. Heating value.
6. Apparent specific gravity.
7. True specific gravity.
8. Porosity.
9. Shatter test.

In the case of the chemical analyses, the methods used are similar to those employed in the testing of coal and in this chapter these methods will be described only in so far as it is necessary to modify the methods that are given under the subject of coal. In this connection, particular reference should be made to the standards adopted by the American Society for Testing Materials[*] to the methods of the U. S. Steel Corporation for the commercial sampling and analysis of coke and to a number of bulletins that have been published by the U. S. Bureau of Mines.

The following determinations are made with such insignificant variations from the methods employed in testing coal[†] that description is omitted in this Chapter.

1. (*e*) Determination of sulphur.
1. (*f*) Determination of phosphorus.
2. Ultimate analysis.
3. Analysis of ash.
4. Fusing point of ash.
5. Heating value.

Sampling.—The correct sampling of coke is a proposition of considerable difficulty particularly where the determination of moisture is important. Good individual judgment is, in most cases, more reliable than detailed instructions but the following general instructions should be observed:

> The coke should be sampled when it is being loaded into or unloaded from railroad cars, ships, barges, or wagons, or when discharged from supply bins, or from industrial railway cars, or grab buckets, or from any coke-conveying equipment, as the case may be. Samples collected from the

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[*] *A. S. T. M. Standards*, **1918**, pages 709 to 720.

[†] See page 1214.

surface of coke in piles or bins, or in cars, ships or barges are generally unreliable.

To collect samples, a shovel or mechanical means should be used in taking equal portions or increments. For any size of coke, the increments taken should be from 5 to 10 lb.

The increments should be regularly and systematically collected so that the entire quantity of coke samples will be represented proportionately in the gross sample, and with such frequency that a gross sample of the required amount shall be collected.

The weight of the gross sample to be taken will depend upon the size of the material to be sampled and in general, the relation of the size of individual pieces to the weight of gross sample should be as follows:

Size of Coke Pieces, Inches	Weight of Sample to be Taken, Pound
2 and over	500
1 to 2	250
½ to 1	125
½ and under	60

Provision should be made for the preservation of the integrity of the sample. Where moisture determination is required the sample should be kept at all times in a tightly covered container.

After the gross sample has been collected, it should be systematically crushed, mixed, and reduced in quantity to convenient size for transmittal to the laboratory. The sample may be crushed by hand or by any mechanical means, but under such conditions as shall prevent loss or accidental admixture of foreign matter. Samples of the quantities indicated in the above table should be crushed so that no pieces will be greater in any dimensions, as judged by the eye, than specified for the sample before division into two approximately equal parts. The gross sample should be reduced by a method similar to that given under coal.

The sample should be crushed mechanically with a jaw or roll crusher,* or by hand on a chilled iron or hard-steel plate by impact of a hard bar or sledge, *avoiding all rubbing action, as otherwise the ash content will be materially increased by the addition of iron from the sampling apparatus, even though hardened iron or steel is used.* Continue the crushing until all the sample passes through a 4-mesh screen, mix and quarter this to not less than 5 lb., again crush the 5 lb. sample to a fineness of 10 mesh; mix and quarter to 400 grams. Transfer this 400-gram portion to the porcelain jar of an Abbé ball mill (the porcelain jars in the ball mill should be approximately 9 in. in diameter and 10 in. high; the flint pebbles should be smooth, hard and well rounded), and pulverized to 60 mesh. When pulverization is complete, pour the contents of the jar on a ½-in. screen and separate the sample from the pebbles by shaking the screen. Reduce the quantity of sample by quartering or riffling to about 50 grams. Pass the entire 50-gram portion through a 60-mesh sieve, pulverizing any coarse particles in a diamond mortar and mix with remainder of sample. Place the 50

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* *A. S. T. M. Standards*, **1918**, 711.

grams of 60-mesh coke in a flat dish and dry in an oven regulated at 105 to 200°C. for at least 2 hr., or until thoroughly dry. This dried sample is then preserved for analysis in a rubber stoppered glass bottle.

In case a ball mill is not available for fine grinding, quarter the 5 lb. 10-mesh sample to 200 grams and pulverize to 60-mesh, by impact in a hard steel diamond mortar. *The use of rubbing surfaces such as a disk pulverizer or a bucking board is never permissible for grinding coke.*

Notes.—The accuracy of the method of preparing laboratory samples should be checked frequently by re-sampling the rejected portions and preparing a duplicate sample. The ash in the two samples should not differ more than 0.4 per cent.

In case the coke is wet, it may be necessary to partially dry the coke before crushing and pulverizing.

Under some conditions of high humidity the dry 60-mesh coke may absorb as much as 0.2 or 0.4 per cent. moisture, if exposed to the air. The dry sample should be preserved in a rubber stoppered bottle and the analyses—especially the determination of volatile matter—should be made soon after drying. If a delay of several days occurs the sample should be redried.

Determination of Moisture.—Take the portion of gross sample, which has been crushed to 1 in., mix thoroughly and rapidly and use 30 to 40 lb. for the moisture determination. For coke less than 1 in. in size, thoroughly mix the sample and without crushing, take a representative sample, 30 to 40 lb., for the moisture determination. An ordinary galvanized wash tub makes a very satisfactory container for drying the sample. Dry the coke to constant weight at a temperature of not less than 105° nor more than 200°C.

Calculate the loss in weight to percentage of moisture, which shall constitute the total moisture in the coke.

Notes.—The allowable difference in duplicate determinations by the same analyst is 0.5 per cent.

It will usually be necessary to dry a 40-lb. sample of coke for at least 6 hr. to obtain constant weight. Much depends upon maintaining a good circulation of air through the oven. The length of time required for drying will vary with different ovens and should be determined for each.

Following is summary of results of investigation of the determination of moisture in coke, by U. S. Bureau of Mines (*Tech. Paper* **148**):

1. Investigation shows that the influence of temperature, time, humidity of drying atmosphere, and fineness of sample on the determination of moisture in coke may be varied over a considerable range without affecting the result appreciably.

2. Oven temperatures ranging from 105 to 200°C. produced a maximum variation in moisture of not exceeding 0.3 per cent.

3. Coke can be dried to "constant weight" without any gain in weight taking place.

4. The circulation of air dried by sulphuric acid, through the oven atmosphere, as specified for coal analysis, is unnecessary, there being no measurable difference of results between circulating perfectly dry air through the oven and using in the oven the natural circulation of air from the room.

5. Moisture can be determined quickly and with adequate accuracy

(±0.5 per cent.) by simply heating to constant weight a large sample of lump coke, in any convenient oven, or on a stove, hot plate, or steam coil at a temperature of 100 to 200°C.

Because of its simplicity and flexibility this method may be used advantageously at points where coke shipments are sampled.

Determination of Volatile Matter.[*]—For the determination of volatile matter in coke, the crucible should be of 10 c.c. capacity, with capsule cover having thin flexible sides fitting down into the crucible. Or the double crucible method may be used, in which the sample is placed in a 10 c.c. or 20 c.c. platinum crucible, which is then covered with another crucible of such a size that it will fit closely to the sides of the outer crucible, and its bottom will rest ⅛ to ½ in. above the bottom of the outer crucible.

Use the dried 60-mesh sample of coke for this determination and proceed according to the method for the "Determination of Volatile Matter in Coal."

The loss in weight shall constitute the volatile matter in the coke.

Notes.—The permissible differences in the duplicate determinations are as follows:

Same analyst	0.2 per cent
Different analyst	0.4 per cent

The results obtained for volatile matter in coke will tend to run appreciably low after the platinum crucible has been used for some time unless the crucible, when not in use, is kept in dilute hydrochloric acid, to remove any iron deposited on the platinum; the crucible should be kept well polished. The life of the platinum crucible will also be prolonged if these precautions are observed.

Determination of Ash.—Weigh 1 gram of the dried 60-mesh coke into an ignited and weighed No. 2 porcelain capsule, ⅞ in. deep and 1¾ in. in diameter, or similar shallow dish or platinum crucible. Ignite to constant weight (±0.001 gram) at a temperature of not exceeding 950°C. in a gas or electric muffle furnace, having good air circulation. Cool in a desiccator and weigh.

Notes.—The permissible differences in duplicate determinations are as follows:

Same analyst	0.2 per cent
Different analyst	0.3 per cent

Before replacing the capsules in the muffle for ignition to constant weight, the ash should be stirred with a platinum or nichrome wire. Stirring once or twice before the first weighing hastens complete ignition.

In case a muffle is not available, a meker burner whose flame temperature is regulated to 950°C. may be used.

It will usually require about 4 hr. to completely burn off all the carbon in the coke.

[*] *A. S. T. M. Standards,* **1918,** 714.

Determination of Fixed Carbon.—Compute fixed carbon in the dry sample as follows:

100 − (ash + volatile matter) = percentage of fixed carbon.

Determination of Nitrogen.—The Kjeldahl-Gunning method is used as in the case of coal, but the decomposition of coke proceeds much more slowly. The sample should be ground to an impalpable powder and even if this is done the digestion may require from 12 to 16 hr.

In order to be certain that the oxidation is complete, digest one determination for 12 to 16 hr. and another for about 30 hr. and if there is any difference between the two determinations, repeat in a similar manner, but increase the length of the periods of digestion. More sulphuric acid should also be added from time to time to replace acid volatilized during digestion.

Determination of Apparent Specific Gravity.—It is very difficult to determine the apparent specific gravity of coke in such a way that the results obtained will be truly representative. The cell structure of coke varies considerably in the different pieces of coke from the same oven or retort and even varies from point to point in the same piece of coke. This variation makes it difficult to obtain small laboratory test samples which will truly represent the physical structure of the coke as a whole.

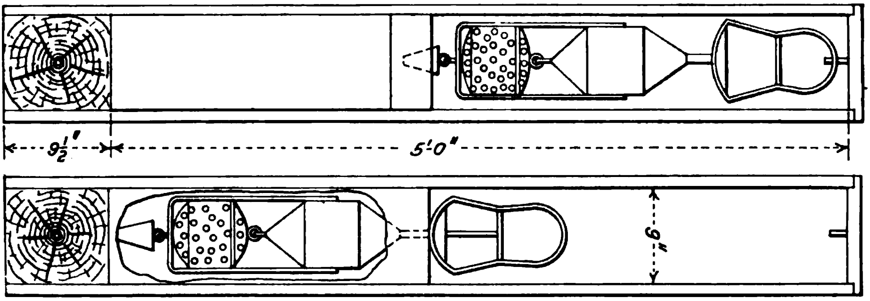

Fig. 57.—Apparatus for apparent specific gravity of coke; United States Bureau of Mines' method.

Where it is necessary to make the determinations on comparatively small samples, test specimens may be broken or cut out of the larger pieces of coke in such a way that they represent the coke from a given position with respect to the wall of the oven or retort; thus in sampling by-product coke, it is customary to take the specimens representing the material between 2 and 3 in from the wall end. The results obtained from these small specimens will compare one kind of coke with another so that it can properly be said that one coke is denser than another or lighter as the case may be, but the results are not necessarily accurately representative of the actual specific gravity of the coke as a whole. However, good judgment with respect to the selection of test specimens will make it possible to obtain results that are fairly close to the average and methods relating to the testing of small quantities of coke have important practical value, because in many cases larger quantities are not available.

Two alternative methods are given for the testing of small samples and one method is given for the testing of large samples.

(A) U. S. Bureau of Mines Method Using 1½- to 2-in. Cubes.—The apparatus used for the determination of the apparent specific gravity consists of a galvanized iron cylinder which is filled with water to the water line, as indicated in Fig. 57. In the cylinder is immersed a hydrometer made of brass. On the top of the hydrometer are two pans. The upper one is used for weights and the lower one for the sample. Below the air buoy is a brass cage perforated with many holes to allow the air to escape when the instrument is immersed. The cage carries the sample when it is weighed under water.

The method of determining the apparent specific gravity is as follows:

Brass weights are placed on the upper pan until the hydrometer sinks to a mark on the stem between the copper pan and the buoy. The total weight required is recorded. The weights are removed, and about 500 grams of the sample in lump form (about 1½- to 2-in. cubes) are placed in the copper dish. Brass weights are then added until the hydrometer sinks to the mark on the stem. The difference in the weights used gives the weight of the sample in air. The sample is then carefully transferred to the brass cage below the buoy. The weights on the upper pan are now adjusted until the instrument again sinks to the mark on the stem. The weight required to sink the hydrometer to the mark with no sample on the upper pan nor in the brass cage minus the weight required to sink it to the mark with the sample immersed in the cage equals the weight of the coke in water. Then,

If the weight of the sample in air $= x$
and the weight of the sample in water $= y$
The apparent specific gravity $= \dfrac{x}{x-y}$

(B) Bottle Method Using 1-in. Cubes.—Select about 20 pieces of coke in which the characteristic cauliflower structure of the ends adjacent to the walls of the oven or retort can be distinctly seen. In testing by-product coke, it is customary to chip from each of these pieces a small cube of approximately 1-in. size representing the material between 2 and 3 in. from the wall end. In testing retort coke, due judgment will have to be exercised to select the test specimen so as to be fairly representative of the average structure of the coke. It is convenient to smooth off the rough edges of the specimens on an emery wheel. Before proceeding with the test, dry the coke thoroughly and brush off any loose dust.

Take a wide mouthed bottle of about 3 or 4 liters capacity and grind the mouth smooth so that it will closely fit a glass plate placed over it. Fill the bottle with distilled water, slip the glass plate over the mouth and wipe off any excess water. Weigh bottle plus water (*A*). Pour out the water, let the bottle drain 30 sec. and weigh, with glass plate (*B*). Put the pieces of coke in the bottle and weigh (*C*). Then fill with water. Let stand for 30 min., shaking now and then to detach air bubbles. Then fill completely, put on the glass plate, wipe off excess moisture, and weigh bottle plus water plus coke (*D*). Remove plate, pour out water, holding hand over mouth of bottle to prevent coke from falling out. Drain 30 sec. and weigh (E). Following are the calculations, the weights, being taken in grams:

$A - B$ = Capacity of bottle.
$C - B$ = Weight of dry coke.
$D - E$ = Equivalent of space between coke and sides of bottle.
$(A - B) - (D - E)$ = Equivalent of apparent volume of coke.

$$\frac{C - B}{(A - B) - (D - E)} = \text{Apparent specific gravity.}$$

Note.—All weighings should be made with glass plate on the bottle.

(C) **Method Using Large Pieces of Coke.**—Select 25 to 30 lb. of coke which should be as nearly representative as possible of the entire quantity under consideration with regard to size, shape and general appearance. Dry coke thoroughly at 105 to 200°C. and weigh when cool after shaking and brushing off any adhering dust (A).

Provide a wash boiler or other suitable container with a spout which may be conveniently formed by soldering in horizontally a short ¾-in. nipple about 6 in. below the top of boiler. The boiler should be placed on a level and rigid base or floor. A wire cage or basket provided with a cover and a long wire handle suitable for holding the entire sample of coke, should also be provided and placed in the boiler.

Place a tightly fitting cork in ¾-in. nipple and fill boiler with water until the water level is above the nipple. Allow the water to come to rest, remove the cork and allow all excess water to drain and replace cork. Remove cage, shaking all adhering water back into the boiler and place the dried coke sample in the cage. Lower the cage and coke into the water and let stand for 30 min. with occasional stirring of coke to detach any air bubbles adhering to the surface of the coke, but without disturbing the position of the boiler. The coke must be completely submerged at all times. At the end of the 30 min., after the water has come to rest, remove cork and allow the displaced water to drain into a weighed container. Weigh the displaced water (B). Quickly remove the cage and coke from the water, allow to drain for 1 min. and weigh wet coke without cage (C).

A = Weight of dry coke.
B = Weight of water displaced by wet coke.
C = Weight of wet coke.
$C - A$ = Weight of water absorbed by coke.
$B + (C - A)$ = Weight of total water displaced and absorbed.

$$\frac{A}{B + (C - A)} = \text{Apparent specific gravity.}$$

Note.—The water should be near room temperature so as not to vary appreciably.

Determination of True Specific Gravity.—To determine the true specific gravity of coke substance, the procedure is as follows: A sample of the 60-mesh coke, weighing approximately 3.5 grams is dried between 105 and 200°C., and introduced into a 50-c.c. pycnometer with about 30 c.c. of distilled water. In order to avoid loss of particles of the sample during boiling, a one-bulb, 6-in. drying tube (*a*) (Fig. 58) is connected with the pycnometer by means of a small piece of pure gum tubing (*c*). The other end of the drying tube is connected with the aspirator. Suction is applied and the contents of the flask are gently boiled on the water bath (*d*) under partial vacuum for 3 hr. in order to expel all air from the sample. The pycnometer is then detached, almost filled with boiled and cooled water, allowed to cool to the temperature of the balance room, completely filled with water at the same temperature, stoppered and weighed. The temperature of the contents of the pycnometer is taken immediately after weighing. Each pycnometer is accurately calibrated and a table is constructed giving its capacity in grams of water at different temperatures.

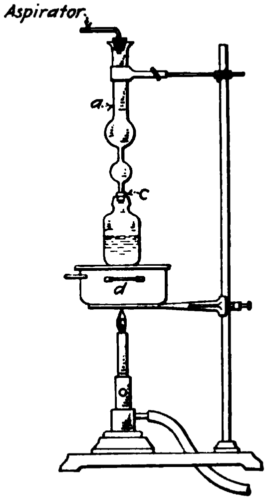

FIG. 58.—Apparatus for true specific gravity of coke.

True specific gravity is determined by use of the following formula:

$$\text{The specific gravity} = \frac{W}{W-(W^1-P)}$$

in which

W = Weight of coke.
W^1 = Weight of pycnometer + coke + water to fill.
P = Weight of pycnometer + water to fill.

Note.—A convenient and rapid modification of this method is the use of benzene instead of water. Suction is unnecessary and boiling may be reduced to 30 min. The determination is very conveniently made in 50 c.c. glass-stoppered volumetric flask. Provision for condensing the benzene vapors may be made by wrapping neck of flask with cloth, which should be kept moistened during the boiling.

$$\text{True specific gravity} = \frac{W\,G}{W-(W'-P)}$$

Where

W = Weight of coke.
W' = Weight of flask + coke and benzene to fill.
P = Weight of flask + benzene to fill.
G = Specific gravity of benzene at temperature at which determination was made.

Porosity.

$$\text{Per cent. by volume of coke substance} = 100 \times \frac{\text{Appearent specific gravity}}{\text{True specific gravity}}$$

Porosity (or per cent by volume of cell space) = 100 − per cent by volume of coke substance.

Shatter Test for Coke.—The apparatus consists essentially of a box capable of holding at least 100 lb. of coke, supported with the bottom 6 ft. above a cast iron plate. The doors on the bottom are so hinged and latched that they will swing clearly away when open and will not impede the fall of the coke. Boards are placed around the cast-iron plate to prevent pieces of coke from being lost.

Each sample is approximately 50 lb. and is selected at random using a 2-in. tine fork. The sample is cool when tested but not artificially dry.

The entire sample, which has previously been weighed, is placed in the box, spread evenly over the bottom and dropped on the cast-iron plate.

The entire material is dropped four times onto the cast-iron plate. The small material including the dust is returned to the box with the large coke each time in order to represent as nearly as possible, the practical conditions to which coke is subjected.

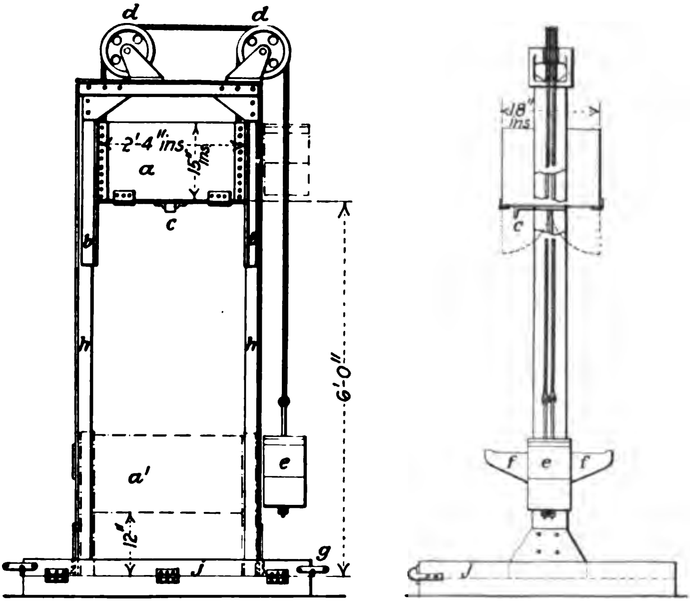

Fig. 59.—Shatter test apparatus.

After the fourth drop the coke is screened on a wire screen with square holes, 2 in. in the clear; the coke that remains on the screen and the portion that passes through are weighed and the breakage is determined. If the sum of the weights indicates a loss of over 1 per cent. the test is rejected and a new one made.

A convenient type of shatter test apparatus is shown in Fig. 59. The box is hung by cable wire over pulleys, which permit the box to be lowered for filling. This arrangement saves the labor and time, that is involved in climbing up to fill the box before each drop.

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CHAPTER IV

BRIQUETTED OR COMPRESSED FUELS

By

G. J. Mashek[1]

HISTORICAL

The briquetting, or compressing, of comminuted coal or other fuel, usually with the aid of some bonding material to hold the finely divided particles together, is an old manufacturing process. It is stated that the briquetting of fuels originated in China, and that, undoubtedly, the briquets were made by hand in the form of balls. Reference has been found to the manufacture of "cole balls" in Germany in 1594, and about the same time Sir High Pratt published a pamphlet suggesting the briquetting of coal. The beginning of the industry frequently has been credited to England, and there is some evidence that it was known and carried on in the time of Queen Elizabeth, according to Wormwalls; but the first published specification relating to fuels of this character in the English Patent Office records is dated April, 1773.

Bjorling gives the following particulars regarding the first coal briquetting installations in different countries. The first briquetting machines were built in France in 1842 (operated at Berard, near St. Etienne); in England in 1846, at Newcastle-on-Tyne; in Belgium in 1852, at Montaguy Sambre; in Austria in 1858, at Brandiste, near Prague; and in Germany in 1861, at Muhlheim-on-Ruhr. The industry then increased quite rapidly in Europe and considerable importance was given to it by the exhibits of briquetting machinery at the Paris Exposition in 1867.

The first attempts to carry on fuel briquetting in America were started in 1870 by E. F. Loiseau, at Port Richmond, Philadelphia, Pa. The equipment used were rolls of the Belgian type, known as the Loiseau rolls. The briquets made were eggette-shaped, weighing 7 to 8 oz. each, and the material briquetted

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[1] President, Mashek Engineering Co., New York, N. Y.

was anthracite culm and a clay binder; these briquets were waterproofed with rosin dissolved in benzine. A considerable tonnage was produced, but the plant was never a success, either mechanically or commercially. Loiseau built another plant at the Philadelphia Centennial Exposition in 1876, using a similar type of machinery considerably improved, making smaller briquets and using American gashouse tar as a binder and also coal tar pitch imported from England. In the same year the Delaware & Hudson Canal Company erected a similar plant at Round Hill, N. Y., which was purchased in 1878 by the American Fuel Company and operated until about 1880. This plant briquetted anthracite screenings, using as a binder pitch made from gashouse tar. Owing to the crude construction of the machinery, the product was never satisfactory, being very smoky and objectionable in many ways, with the result that this venture was not a commercial success. Subsequently another plant was built at Mauch Chunk, Pa., which was equipped with the Loiseau roll-press somewhat improved, using the same binder; but the product was unsatisfactory and the result was that the operations was discontinued.

The next installation in the United States was made in 1890 at Mahoning, Pa., by the Anthracite Pressed Fuel Company. In this plant there was installed a Stevens press manufactured in England, which made a 2-lb. briquet; its capacity was 300 tons per day. The binder was pitch made from coke-oven tar imported from England. However, the briquets were objectionable on account of the large percentage of this binder used, and also because of their high-ash content, and the plant was closed down in 1892. Notwithstanding these facts, a considerable quantity of product was made; and while it was found difficult to sell the briquets for domestic and steaming purposes, on account of their poor quality, the product was consumed in locomotives of the Reading Railroad.

W. B. Gay, of Gayton, near Richmond, Va., erected in 1892 a briquetting plant using a Loiseau type of press, for the purpose of briquetting Virginia semianthracite slack, or so-called natural coke, using coal tar pitch as the binder. This plant must have been fairly successful for the reason that it was doubled in size later on. Similar plants were erected at about this same time in Milwaukee and Chicago for briquetting anthracite dust and bituminous slack. Since all these plants were abandoned later, although the Chicago plant was used also for briquetting iron ore for the Illinois Steel Company during the summer months, it is evident that they were not commercially successful.

The greatest advance in the perfection of machinery and processes up to this time was made by M. Nirdlinger in 1895, and the National Eggette Coal Company of New Jersey erected a plant at Huntington, Ark., in accordance with the Nirdlinger patents, briquetting Arkansas semianthracite and bituminous coal, using coal tar pitch as the binder. The cause of the failure of this plant was that it was located in a part of the country where coal was comparatively cheap and it really gave better results than the briquets on account of the odors and the smoke produced by combustion of the coal-tar pitch in them. Shortly after that time a number of small experimental plants were erected in different parts of the country, all of which proved to be failures.

The next attempt to develop the briquetting industry was in California, where considerable progress was made. A plant was erected at Stockton, Cal., to briquet lignite from the Tesla mine. Some bituminous screenings were mixed with the lignite, and the binder used was asphalt residuum. This plant was located on the pipe line running to Oakland from the Californian oil fields, and the asphaltum was obtained by distillation from the crude petroleum, the oil being pumped back into the pipe line. The press was of the rotary plunger type, designed by Robert Schoor, of San Francisco. This plant made very good-looking, clean briquets; but, on account of the improper treatment of the lignite and its poor quality, as well as the high cost of manufacture, it was never a commercial success. The plant burned down in 1905 and has not been rebuilt. Other plants were erected at Oakland, Cal., by the Western Fuel Co.; at Pittsburg, Cal., by C. R. Allen; at Oakland, by the Standard Coal Briquetting Co.; and in San Francisco, by the American Briquetting Co.; but all these undertakings have either failed or have been given up.

In 1906, a plant was built by the New Jersey Briquetting Company in Brooklyn, N. Y. It was later moved to Perth Amboy, N. J., and was equipped with a Mashek press, using coal-tar pitch as a binder. In Brooklyn the briquets were baked so as to make them smokeless. This undertaking apparently was successful until conditions changed, when the operation of the plant was stopped. The first commercially successful briquetting plant in the United States, having a maximum capacity of about 20 tons an hour of 2¼-oz. briquets, and equipped with Mashek equipment, was built at Superior, Wis., by the Scott Briquet Company. It has been in continuous operation up to the present time and recently its capacity has been doubled with the same type of machinery. The material briquetted is anthracite and bituminous slack coal, mixed, using asphaltum as a binder; and a practically smokeless briquet is produced which is used solely for domestic purposes.

Since 1906 a number of other plants have been erected in Canada and in different parts of the United States, and many of them are in continuous operation. In recent years new processes have been developed, machinery has been improved and standardized, and smokeless and odorless binders have been developed, so that today the briquetting of fuels is an industry with a technology.

BRIQUETS

The term "briquet," as applied to and now universally used for all forms of compressed fuel, originated in France and is given to fuel made from peat, lignite and coal, produced either with or without a suitable binder. The word "boulet" is also of French origin. In England, compressed fuel is known as "patent fuel," in Germany "kohlensteine," and other names, such as eggettes, stone coal, pressed fuel, artificial fuel and boulets, have been adopted in America by different manufacturers to designate their products. However, the word "briquet," as it is understood at the present time, relates to and covers any manufactured solid fuel, whether with or without binder, or smokeless.

The Advantages of Briquets.—In reference to the superiority or greater heating value of briquets, as compared with the lump or prepared sizes of the coal from the dust or breakage of which they are made, it may be stated generally that, if the briquets are manufactured properly of the right size and shape (governed by the coal they are made from and use put to) and of the required hardness, almost regardless of the kind of material used for a binder, as long as it does not add ash, the briquets will give during combustion or in use from 10 to 30 per cent more available heat than the same weight of the prepared sizes of lump coal mentioned. This increase of heating value during combustion is not due to any increase of calorific value of the fuel in passing through the briquetting operation. The calorific value of briquets, when made with combustible and all-carbon binders, usually is increased from 3 to 7 per cent, due to the addition of a binder such as coal-tar pitch, asphaltum, tar or oils; it also depends on the process used and the elimination or drying out of any excess moisture that the coal may contain in its natural state. With the exception of peat, lignite, subbituminous coal and some high-volatile coals, the mere operation of briquetting does not change the character of the coal. The increased heat obtained from a given weight of fuel when briquetted, in comparison with the same weight of prepared sizes of coal, is due to better and more perfect combustion of the coal in the briquetted form than in its natural state. For instance, taking the extreme case, in the anthracite-consuming part of the country, the average amount of carbon remaining in the ash and clinker from anthracite coal varies from 15 to 40 per cent, whereas, under the most adverse conditions, briquets made from this same coal, when burned under identical conditions, will show that the ash contains only from 4 to 6 per cent of unconsumed carbon. The size of the briquet, the coal it is made from, and the type of furnace it is used in, have important bearings on the results obtained.

The additional advantage of briquets, especially in domestic use, is that they burn on the surface only, and a partly consumed briquet is, as a general rule, perfectly black on the inside and, if properly made, should be as hard as it was at the beginning. It will ignite and burn practically as freely as a new briquet, whereas it is almost impossible to ignite and consume the unburned portion of carbon screened from the ash obtained from the ordinary prepared sizes of coal. While this screening of ashes is practiced to a considerable extent, especially in the eastern part of the country, it is doubtful if any advantage or benefit is derived from the screened product containing the amount of unconsumed carbon mentioned above.

The Size and Quality of Briquets.—A commercially successful briquet must be harder and break less during transportation and handling than the coal from which it is made; in fact, all briquets should be able to stand as much handling, with no more breakage, no matter from what coal they are made, as the best quality of prepared sizes of anthracite coal. A briquet should stand weathering so as not to deteriorate or soften, and should not absorb over 3 per cent of moisture. All properly made briquets should improve with age, especially if tar, coal-tar pitch, oil or asphaltum is used as the binder.

Almost from the inception of the briquetting industry in Europe, the importance of the size of briquets has been recognized. Briquets are practically all manufactured in two types of presses, the plunger and roll types. The mode of operation of tue plunger press is first filling the mold with the desired quantity of prepared material, then compressing, and finally ejecting the compressed briquet. This type of press is built to make briquets usually accomplish these movements in one revolution of the press and fill one mold at a time. The difficulty in operating a press where a number of plungers are attached to a platen is to get the molds filled with an equal weight of material so that the pressure exerted on all briquets is alike. The plunger type of press has not been successful on this continent, but still is used extensively in Europe, producing, as a rule, large briquets that are handled by hand like building brick. However, this type of press is gradually being replaced by the rotary type, which produces smaller briquets, principally for the reason that the price of labor is rapidly increasing all over the world, especially since the War, and always has been too high in this country to permit the careful stacking and piling up of the product in this shape. These large briquets, when used for domestic purposes, must be broken up with a hatchet or ax for stoves and very often for steaming purposes, and this operation produces dust and breakage. In Europe there does not appear to be a serious objection to the breaking up of the briquet, especially for domestic use, on account of the high price of prepared sizes of good coal. Indeed, in many parts of Europe the best fuel that can be obtained is a rather poor quality of briquet that could not be marketed in this country. In the United States there are no people, even among the recent immigrants, who care to go to the trouble of breaking up a briquet. The general demand is for a size of briquet from which the same results can be obtained as from the prepared sizes of fuel the public is in the habit of using. One manufacturer in New York expended nearly $100,000 on a plant equipped with European machinery, using coal tar pitch as a binder and making large briquets. The undertaking proved to be a failure, for he found that on account of their size, they could not even be given away to the poorest people in New York City.

The other process of making briquets is bym eans of two rolls, in which depressions are machined to produce the size of briquet desired, and a number of machines have been developed on this principle. The idea of using roll presses is credited to the Belgians, and all rolls are either exact duplicates of the original Belgian roll, producing eggettes, or a modification of that principle, making an improved type of press to get better pressure, positive discharge and a product with less waste. As stated in the beginning of this Chapter, in this country Loiseau was the first to introduce this type of press, which is built to produce practically any size of briquet. It also consumes less power, makes a better shaped briquet for shipping purposes than the plunger type of press, and the cost of renewal of wearing parts is usually but a fraction of that of the plunger press to produce the same tonnage. The pressure under which briquets are made in the press varies, as experience has shown advisable, from 1,800 lb. per square inch for soft and easily crushed coals, up to about 3,000 lb. per square inch for hard anthracite, using patented or smokeless binders.

While the press is a very important part of a briquet plant equipment, because it is the machine that finally makes the product, the success of any briquetting proposition depends more on the installation of suitable equipment for properly preparing and handling the coal and mixing the binder into the material and getting it to the proper temperatures and consistency, ready for the press. It is this latter part of the plant that has caused most of the failures and difficulties of the past.

A briquet must be of such form or shape that it can be spouted or handled with clam-shell buckets, shovels, elevators, etc., the same as ordinary coal, and must contain as few sharp edges or corners as is possible, so as to eliminate breakage or abrasion. A great deal of time and money have been spent in trying to develop a shape of briquet that would give the best results. In free-burning or soft coals and lignites the eggette shape seemed to afford the best results, giving the proper amount of air space for the combustion of gases and admission of air, the size of eggette depending upon the use. It has been found, however, that the eggette shape above 2 oz. in weight has too much air space, especially when made of anthracite coal. Many other shapes have been tried without obtaining any better results. To overcome this objection to small eggette shapes, the over-stuffed-pillow shape briquet was developed, and it has given better results, no matter of what kind of coal it is made or what binder is used. The important point that must be considered with any shape is the right size to give the best results with different coals and the purpose for which the fuel is intended. At the present time the prevailing sizes that the public, after considerable experience, demand, vary from 1⅝ oz. to 2½ oz. for domestic use and from about 2¼ oz. up to 5 oz. for steam or furnace use. The larger size is only suitable for steam boilers and large furnaces, and it has been found in burning briquets in locomotives that the 2-oz. to 2¼-oz. briquet, when made from so-called semi-anthracite, high-carbon coal dust, gives better results than a 3¼-oz size and less carbon monoxide in burning.

THE PRESENT OUTLOOK

The present conditions in America point clearly to a rapid increase in the manufacture of briquets, for the reason that the experimental or developmental stage of the industry has been passed to such an extent that today briquet plants can be designed and erected to handle any kind of coal successfully at a known cost and value of the briquetted material, without any additional experimenting. The development of this industry in America has been retarded to a considerable extent by the failure of a number of plants equipped with European machinery which, while successfully operated abroad, failed here for the reason that the product was not of satisfactory size and quality to meet the requirements of the American public. In Europe almost anything that will hold together and burn in that form is more readily sold, on account of no better quality of natural fuel being available; whereas on this continent briquets must compete with the very best fuels obtainable in the world, and in order to compete they must have some advantages either in quality or price, the first requisite being quality. All European equipment, imported and installed here, has turned out to be industrially unsuccessful, and no plant is in operation which is equipped with European machinery as it was originally imported. In the meantime, American manufacturers have developed machinery and processes that are entirely new and that do produce the desired results, as is evidenced by the increasing number of successful plants being installed each year.

In the past, on account of the immense deposits of coal in the United States, improved methods of mining, comparatively cheap labor, and low costs of transportation, very little attention was paid to the breakage usually left as waste at the mines. This was considered, until very recently, of practically no value— in fact, a nuisance— but with the consumption increasing every year, the higher costs of labor and transportation, the gradual education of the people to the proper combustion and handling of fuel, and the higher cost of living, a field has opened for the manufacture of briquets on the American continent that will increase from year to year, especially in the lignite fields. In the lignite branch of the industry important developments and improvements have been made, so that this fuel of inferior value and low price can be converted into a manufactured product which is practically equal to anthracite in all respects and which will stand storage equally as well.

BRIQUETTING PROCESSES*

In order to give in this limited space an account of the processes that coal must be put through in order to be converted into briquets, there are presented several flow sheets, which indicate the course of the coal and the binder through a modern briquetting plant, and the different operations to which the coal is subjected in order to make a first-class product. These flow sheets begin with the raw product at one end and show the finished product delivered at the other end, and are only general in their character inasmuch as in each case each coal must be analyzed and its character carefully studied, as well as the kind of product desired, capacity of plant, etc. These processes also may vary in different installations. All plants should be built in such a manner that additional like units can readily be installed in the future, if so desired; and the buildings should be designed so that they can be extended to cover any number of additional units and make the whole symmetrical, convenient to operate, and additions can be made without disturbing any part of the plant already erected and in operation.

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* For further information on this subject, see G. Franke's "A Handbook of Briquetting" (translated by F. C. A. H. Lantsberry), 2 vol. P. R. Bjorling's, "Briquettes and Patent Fuel," 1905, gives attention to binders other than coal-tar pitch and asphaltum, and also presents 121 illustrations of different types of machinery in use about 20 years ago.

Figure 60 shows the arrangement of a briquetting plant to use coal tar pitch or asphaltum in a melted or liquid state as the binder, the binder being received in tank cars provided with heating coils. The coal dust usually is delivered to the plant, if at the breaker, by means of scraper conveyors or in mine or railroad cars, the plant being arranged so that the car can be dumped into an elevator pit, the elevator handling the material from that point automatically. The plant must be automatic from one end to the other, in order to minimize the cost of labor.

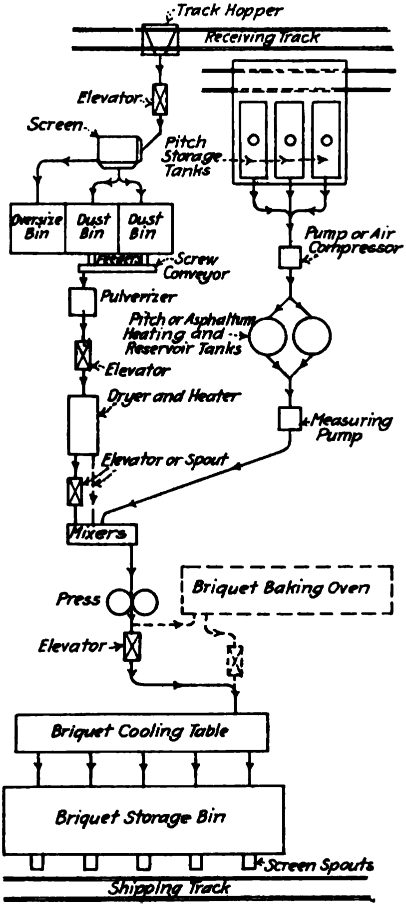

FIG. 60.—Briquet plant to use melted pitch or asphalt binder.

Where pitch or asphaltum is used as the binder, and with the use of many other classes of binders, the coal must first be crushed to a suitable size for briquetting. This size varies with the hardness and quality of the coal briquetted and the quality and purpose for which the product is intended. All the coal must pass through from an 8- to 16-mesh mining screen.

The coal to be briquetted, experience has shown, almost irrespective of the kind of binder used, must be dried at least sufficiently to produce a perfectly dry surface on each particle of the coal. This depends on the coal and the degree of drying required, and is sometimes done before the pulverizing and sometimes afterwards. Recently pulverizers have been perfected for briquetting plant purposes that will handle coal with any amount of moisture up to the consistency of mud. These pulverizers are constructed so that no screen is necessary to return the oversizes, as the screen to handle this small mesh material suitable for briquetting would have to be very large, occupy considerable space in the building, and require power and attention to operate. Hence the pulverizer must be equipped to produce an even size product without the necessity of screening. The product is easier to dry and heat after it is pulverized to the right size, for there are no large pieces to be heated through and less danger of burning the small particles. The type of dryer most suitable for this purpose depends on the moisture content and the character of the coal. Dryers of the steam type, indirect heat and direct heat types, are used. The amount of moisture to be removed from the coal to be briquetted depends on the coal and the binder used and varies considerably. In some coals as much as 3 per cent of moisture can be left in without affecting the quality of the briquets, while on other coals and in other processes which are used the coal must be "bone dry," or contain not over 0.25 to 0.50 per cent of free moisture. In the high-volatile coals it is very often advisable to expel part of the lighter volatile matter, since very little or no benefit is derived therefrom, especially in domestic use; thereby increasing the fixed-carbon content, which makes a harder briquet for storage and a longer lasting briquet in combustion.

In Fig. 60 is shown in dotted lines at what point an oven should be installed, if it is desired to make either partially or entirely smokeless briquets. Entirely smokeless and odorless briquets can be produced only from smokeless coal. A large portion of the smoke-forming substances in bituminous coal usually can be eliminated by partial distillation in suitable appliances and baking or heating the briquet after it is made so as to distill or drive off some of the lighter volatiles of the binder.

All plants that are erected away from the mines and expect to use different coals in the manufacture of their product, should be equipped with two or more raw material dust bins, each equipped with a variable controlled feeder, so that different qualities of coals can be mixed in any proportions desired. There are many deposits of coal throughout the country which alone do not produce a satisfactory briquet, but very often a mixture of two more or less inferior coals give a high-grade briquet.

The amount of binder used has a very important bearing on the quality of the briquet produced, and it is always desirable to cut down the quantity of the binder as far as possible. Many processes have been patented, such as atomizing the pitch into the coal dust in the mixer or mixing it in the form of an emulsion with water, in order to spread it over as large an amount of dust as possible, both of which processes have failed to accomplish the desired results on a commercial scale. Most manufacturers have some method, often patented, or secret processes of introducing the binder in a liquid or pulverized state, so as to use a minimum quantity. The hardness of the briquet depends to a great extent on the amount of binder used, and an offhand test that is now accepted by many manufacturers and dealers is that 1⅝ to 2 oz. briquets should be able to bear the weight of a 150-lb. man standing with his heel on the briquet without crushing it; there are also various rumbling and drop tests in use.

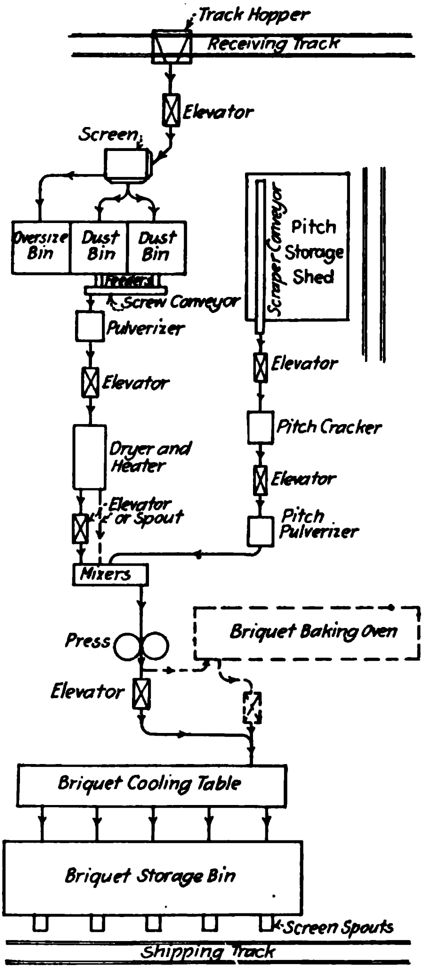

FIG. 61.—Flow Sheet No. 2.—Briquet plant to use pulverized pitch or asphalt binder.

The question of whether to use pitch in a melted state or in a dry pulverized condition, and at what melting-point, must be left to those who have had experience, for the reason, as stated above, that these requirements depend on the character of the coal and hardly any two deposits of coal are alike. As a rule, it is not advisable to use the liquid or melted method for binders with a melting-point above 170°F. (ring and ball test), depending on the kind of coal.

Figure 61 shows a plant arranged to use either coal-tar pitch or asphaltum in a pulverized state. The arrangement of the remainder of the plant is very similar to that illustrated in Fig. 60. Material of a melting point from 160° up to 225°F. can be used in this manner, but it is necessary that the binder be pulverized to from 30- to 50-mesh, in order to get a better distribution and to use a smaller amount. In some cases the coal and binder are fed together into a pulverizer and crushed together. This is more or less an objectionable and wasteful method for the reason that parts of the binder will remain in as large particles as the largest piece of coal that passes through the pulverizer, since there may be difficulty in the spreading of this pitch in the mixer. To use pulverized pitch, higher heats are necessary, and in all cases the briquets should be run over a cooling table before being deposited in a bin or car, so as to allow the binder to set and harden slowly.

The amount of binder which is necessary to make a hard, merchantable briquet varies from 5 to 7½ per cent, depending on the coal and the purpose for which the briquet is intended. The higher the melting-point of the binder, the less effect will climate have on the briquet. All briquets made with asphaltum or coal-tar pitch as a binder, that have not been baked or in which the binder, after being incorporated in the briquet, has not been distilled further or dried in an oven, will soften slightly immediately on ignition until distillation of the lighter volatiles of the binder takes place in the fire, after which the briquet should be practically as hard as when cold and should maintain its shape until entirely consumed. There are a number of other binders used in addition to those mentioned, many of which produce smokeless, odorless and waterproof briquets. The process used in all such cases is slightly different from that shown. The plant in each case, of course, must be built and arranged to use a particular binder, and space does not permit the inclusion of various diagrams to illustrate the different plants that have been erected to use other binders. The subject of binders is discussed at more length *infra.*

THE BRIQUETTING OF ANTHRACITE

The problem of briquetting anthracite culm or waste produced in the eastern part of Pennsylvania really has been the foundation on which more briquetting plants have been started and more effort has been made to briquet than in the case of any other fuel. The principal reason is that this anthracite culm and the dust caused by breakage during the preparation of the mined anthracite are practically useless for almost any other known purpose. At most of the mines these materials are the cause of considerable expense to dispose of The other reason is that anthracite coal, on account of its cleanness and smokeless quality, commands the highest market prices in the country for domestic use; and, of course, the apparent or expected profit in manufacturing this culm or breakage into briquets has offered the best field, especially for promoters and persons with an inventive turn of mind. In addition to the large stocks of culm at the mines, a great deal of which is clean enough to briquet as it is, without any further treatment, there is produced annually in the anthracite region between four and six million tons of dust or breakage, a by-product of practically no value, as stated. Attempts have been made in recent years to dry and pulverize this dust still finer, with the object in view of burning it in locomotives, large furnaces, etc., in the pulverized state, as bituminous coal is used, but little progress has been made in this direction, on account of the low volatile content and high flash-point of anthracite coal when pulverized. By mixing from 20 to 40 per cent of high volatile bituminous coal with anthracite, the mixture then can be burned on ordinary grates, as the coking qualities of the bituminous coal hold the anthracite together until consumed. This mixture can be burned in a pulverized state, since it contains sufficient volatile matter to carry on combustion in a suspended condition in the furnaces. This mixing is carried on to some extent in certain parts of the country, usually where the anthracite dust is of little value.

The first attempts at briquetting this material for the market were made with coal-tar pitch or coal-tar for binder, without baking or distilling the objectionable materials, such as cresols and other lighter volatiles of this binder after it was in the briquet form. The result was that here was the best coal for domestic purposes, which, by the introduction of this binder, was converted into as poor a quality of fuel for domestic use as bituminous coal, and most of the producers tried to dispose of it in that state at anthracite coal prices. Very little anthracite coal is being briquetted today. Several plants are operated, however, which produce an entirely smokeless and odorless product that compares favorably with natural anthracite coal, both as to quality and prices. In fact, the briquetting of anthracite presents as good a field for this industry as there exits in the country.

THE BRIQUETTING OF BITUMINOUS COAL

Bituminous coal can be briquetted readily with practically any binder. The briquets made from bituminous coal invariably will produce less smoke during combustion than the prepared sizes of the same coal from the dust of which they are made; in fact, most bituminous coals will make briquets which will produce smoke only on ignition, after which the briquets are superior to those made from anthracite coal in heating value and very often equivalent in lasting qualities. Some of the secret or patented binders cannot be used for briquetting bituminous coal, on account of its content of volatile matter. Bituminous coal, when well-dried and possibly heated up to 450°F. (which has a tendency to expel some of the lighter volatiles), then briquetted, using some such staple binder as asphaltum, and dried so as to harden the briquets and expel all the moisture of briquetting, makes a very nearly smokeless fuel which will retain its shape until consumed. In fact, bituminous coal, properly briquetted, is preferable for domestic purposes to sized Pocahontas coal. Bituminous coal must be carefully handled in the briquetting plant, and the plant must be designed properly, especially for handling coal the dust of which is explosive.

Where bituminous mines are located convenient to the large industrial centers, it is, as a rule, not advisable to briquet coking bituminous coal, for the reason that it can be converted into coke at less cost per ton and all by-products recovered. Where coking coal bituminous mines are located long distances from the centers where there is a market for coke and its by-products, this condition, of course, changes. For non-coking coal slack and dust, briquetting is really the only method of utilization, unless some of the recent processes, which are still in experimental stages, are successful. Reference is had to the procedures which operate on the principles of first partially carbonizing the bituminous coal, recovering the by-products, then briquetting the carbonized material with coal tar pitch obtained from the first distillate, and finally completing the carbonization of the coal in the briquetted form, recovering all the by-products, and producing a briquet which is low in volatile matter. These products should be comparatively as clean as anthracite and higher in heating value, and make a good domestic fuel.*

COKE BREEZE

There is no difficulty whatever in briquetting coke breeze or braize, but this is not carried on to any great extent for the reason that coke breeze, or dust, especially that from beehive ovens or old by-product ovens, contains a considerable percentage of ash, is very abrasive and destructive to the machinery, does not burn freely, and the only practical way to use it in a briquetted form is to mix it with a percentage of good quality of coal. Coke breeze alone can be converted into entirely smokeless and odorless briquets, but of comparatively low-calorific value.†

CHARCOAL

Several plants have been erected in the tropics to briquet the breakage of charcoal at the kilns. Charcoal briquets are in all cases used for domestic purposes in that territory, must be absolutely smokeless and odorless, and, when made of suitable size, properly put up, usually command a better price than lump charcoal.

PEAT

The briquetting of peat, carried on to some extent in Europe, has been experimented with in this country and Canada on an extensive scale. Large amounts of money have been spent in experimental work; but, to the best of the writer's knowledge, there is not a successful peat briquetting plant in operation in the United States or Canada today, principally for the reason that, under the best conditions, peat briquets contain only 6,200 to 8,000 B.t.u. per pound, the cost of manufacture is fully twice as much as in the case of briquets made from anthracite or bituminous coal, the results obtained are very little better than with wood, and, even in the remote regions where it was expected that the development of peat briquets would give the consuming public a cheaper fuel, they have been found to be more expensive than a good quality of coal. One of the successful ways of treating peat for fuel purposes is to carbonize it, save

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* See, *e.g.*, "carbocoal," p. 441.

† See p. 124.

the by-products which are valuable and will pay a good profit on the cost of operating the complete plant, and then briquet the residual charcoal, which will command in the United States and Canada from $12 to $20 per ton, depending on the location. The only drawback to the development of this industry on this basis is the high cost of the plant required.

Many other methods of utilizing peat for power purposes have been tried from time to time, such as utilization in gas producers and burning in special furnaces for heating purposes; but none of these tests has resulted in any wide use of this fuel. A new process, which apparently has passed the experimental stage, of burning peat directly in contact with the water under pressure, shows a very high efficiency and may be developed into a commercial success. In this instance the high water content of the peat, averaging from 60 to 90 per cent, in its raw state as excavated from the bog, is not detrimental, since more water must be added; but for ordinary combustion purposes this water must be reduced down to 20 or 25 per cent. before peat will burn so as to give any effective heat.

LIGNITE

According to the United States Geological Survey, as well as information obtained from many State geological surveys, there is a greater tonnage of lignite deposits in the United States and Canada by a considerable margin than all other coal deposits combined. Most of the lignite, with perhaps the exception of that of the Pacific Coast, is in States which, until recently, have been more or less sparsely settled and which have no big industries that require large quantities of cheap fuel; but, of course, it is argued that the lack of cheap fuel has hindered the establishment of industries in these States. With the increasing cost of higher-grade fuel and the higher cost of transportation, the necessity for developing the lignite deposits so as to produce a better quality of fuel than raw lignite itself, is rapidly increasing. The problem of converting practically any lignite into fuel equal to Pennsylvanian anthracite in heat value has been solved, and it is in this field that the greatest development of briquetting and by-product carbonizing will take place in the immediate future.

The briquetting of lignite, especially in Germany and Czecho-

Slovakia, is an extensive industry, and both raw and carbonized lignites are briquetted. Where the raw lignite is briquetted, it is necessary to use a large percentage (as much as 9 to 11 per cent) of coal-tar pitch, in order to cover the coal particles so that further air-slacking will not take place and cause the briquets to disintegrate. The results obtained during combustion, however, are very little, if any, better than burning raw lump lignite; in fact, the briquetted fuel is very dirty and smoky, and in no part of this country could it be sold at the present time.

There are briquetting plants in operation in Europe, although gradually being replaced, wherein the lignite is briquetted without the addition of any binder. Partial drying, heating and sweating of the raw lignite are carried on so as to bring out or soften some of the pitch that it contains, then it is subjected to a high pressure and allowed to cool. This makes a very neat briquet that apparently stands weathering, but during combustion no better results are obtained than in burning lump lignite, for the moisture still contained in the lignite, when freed on combustion, causes a large portion of the lignite to crumble to dust on the grates.

The Bureau of Mines has installed a briquetting plant of German manufacture, to carry on experiments with the object of briquetting lignite without the use of binder. From reports published, while this plant cost upwards of $56,000.00, its capacity is only 3 tons per hour, making about 1-lb. briquets of a shape that is not easily handled or spouted. An additional amount of money has been expended in experiments with different lignites in the United States, with the result that this work has been abandoned by our Government and no advance has been accomplished that will aid the development of the lignite industry in this country.

In Europe a great deal of experimental work has been done in the carbonization of lignite, which has developed into a large industry. Valuable by-products are obtained by this process, and the carbonized material, when properly reduced and briquetted, is equal to briquets produced from anthracite coal, and can be made just as smokeless. Very little has been done in this direction in the United States.

The State of North Dakota, through the Mining Department of the State University, has expended considerable time and money on the development of a suitable process for the conversion of lignite into a higher grade fuel. This work has been carried on for about eleven years. An experimental plant having a capacity of from 2 to 4 tons an hour of about 2¼ oz. briquets has been installed. For the treatment of the raw lignite, different types of partial and complete carbonization retorts have been experimented with, including a standard type of bituminous coal gas-bench with a cast iron retort chamber. Retorts of the beehive coke oven type and other vertical types were constructed for partial and complete carbonization. Considerable quantities of briquets have been produced and tested out in industrial and domestic use, and some of the best lignite briquets made of partially carbonized and completely carbonized lignite have been produced at this plant. Some of the results of these investigations and tests have been published by the University of North Dakota in a report entitled "Investigations on Lignite Coal Relative to the Production of Gas and Briquets." Another pamphlet, Bulletin No. 89, U. S. Department of the Interior, 1915, published further results of the work done by this University. The author of both publications is E. J. Babcock, Dean of the School of Mines. The first publication is only very general on this subject; the second goes into this matter considerably further and also gives a number of analyses of gas obtained from different methods of carbonizing lignite and at different temperatures. No conclusions or data have, however, been issued on which could be based the construction of commercial plants for the carrying out of any of these methods. Nevertheless the work accomplished is very interesting, and the results obtained are valuable.

The Laboratory of Industrial Chemistry of the University of Washington, Seattle, Wash., has also carried on investigations on lignites. Some of the results were published* and dealt with the complete carbonization of lignite in a small electrically heated retort. This report gives a very thorough analysis of the by-products, which should be of considerable value in the designing of larger commercial plants.

The University of Texas Bureau of Economic Geology and Technology, under Prof. Wm. B. Phillips, Director, has also carried on investigations on the utilization of lignite; and while no plant has been erected or any large amount of money spent,

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* H. K. Benson and L. L. Davis, *Journal of Industrial and Engineering Chemistry*, **9**, No. 10.

the University has published a very creditable report* on lignite analyses, including by-products, etc., that is of value in connection with the future development of this industry. This is the first work appearing in this country in which ultimate analyses are given of the by-products obtained principally from Texas lignites, under proper and scientific principles.

The Government of the Province of Saskatchewan, Canada, has also expended considerable money in carrying on investigations looking toward the better utilization of its large lignite deposits. The work has been conducted under the direction of S. M. Darling, and the results of the first researches were published by the order of the Legislative Assembly in 1915. No particular effort was made in this investigation to develop a briquetting process, but practically all the research was centered on the preparation of the lignite so as to change it to a fixed fuel by means of drying or carbonizing. Darling constructed a carbonizing retort somewhat similar to those used in Czecho-Slovakia and Germany, with the addition that it was designed and built to eliminate labor as much as possible. No plant was installed or any effort made to work out the best method of recovery of by-products or to determine the quantity and quality of the by-products that could be recovered. The principal object in this case was to produce a high-grade quality of carbonized lignite, which was accomplished. A considerable quantity of the carbonized lignite was screened. The sizes running over ¼-in. mesh screen were sold for domestic purposes and use in gas producers to operate gas engines. In this latter field properly carbonized lignite gave better results than anthracite coal. Some of the residue passing through ¼-in. mesh screen was shipped to different briquetting plants in the United States and Canada, for the purpose of obtaining the results from different processes, presses, sizes of briquets, etc., to determine the value of the briquetted lignite. Some of these results, as far as briquetting of carbonized lignite went, were very satisfactory. The report of the results of these investigations contains a number of proximate analyses of Saskatchewan lignite.

The Canadian Government in 1918 appropriated $400,000.00, to be expended in carbonizing and briquetting tests on southern Saskatchewan lignite for domestic use. This work has been carried on by the Lignite Utilization Board of Canada and

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* *Bull.* No. **307**, Dec. 22, 1913.

laboratory experiments have been conducted at Ottawa for almost two years under the direction of Edgar Stansfield and Ross E. Gilmore. On the basis of these investigations, the Board has erected and equipped about a 20 ton per hour lignite partial-carbonizing and briquetting plant at Bienfait, Saskatchewan, which is expected to be put in operation about September, 1921. It has been announced that it is only intended to convert lignite into domestic fuel by partial carbonization and briquetting in a new type of retort developed at Ottawa. The work on this plant is under the direction of R. Del. French. The literature so far published by the Dominion of Canada is Report No. 1, "The Briquetting of Lignites," by R. A. Ross, Ottawa, 1918. The *Transactions of the Royal Society of Canada*, (3), 12 (1918), contains results by different methods of carbonization and briquetting of lignites written by Edgar Stansfield and Ross E. Gilmore.

A small plant was erected in 1914 at Minot, N. D., with a capacity of 10 tons an hour, for the purpose of briquetting carbonized lignite. For carbonizing the lignite there were erected ordinary beehive ovens and the process of carbonizing was the same as the beehive-oven coking of bituminous coal. The results obtained from this carbonizing installation were very unsatisfactory. The labor cost was almost prohibitive; by-products were all either consumed or wasted; and on account of the construction and the principle of heating the retorts by means of combustion of part of the fuel, a portion of the carbonized lignite was partially consumed and a considerable quantity was only partially carbonized. For these reasons the undertaking was not a commercial success. The carbonized lignite that was obtained was converted into briquets weighing about 2¼ oz. each, of the over-stuffed-pillow-shape. In addition to the treated lignite, there was added about 6 per cent of bituminous coal, and an additional feeder was installed to supply anthracite screenings, of which there was a small amount available from the coal yards, docks, etc. The binder used was either coal-tar pitch or asphaltum introduced in a melted state. The briquets were of the required hardness, gave excellent results in domestic use, and several thousand tons of the product were sold throughout the northwest in competition with anthracite and prepared sizes of Pocahontas coal.

There have been a number of attempts made in Texas, as well as on the Pacific Coast, as stated above, to briquet lignite in its raw state as mined, but apparently none of these undertakings has been a commercial success.

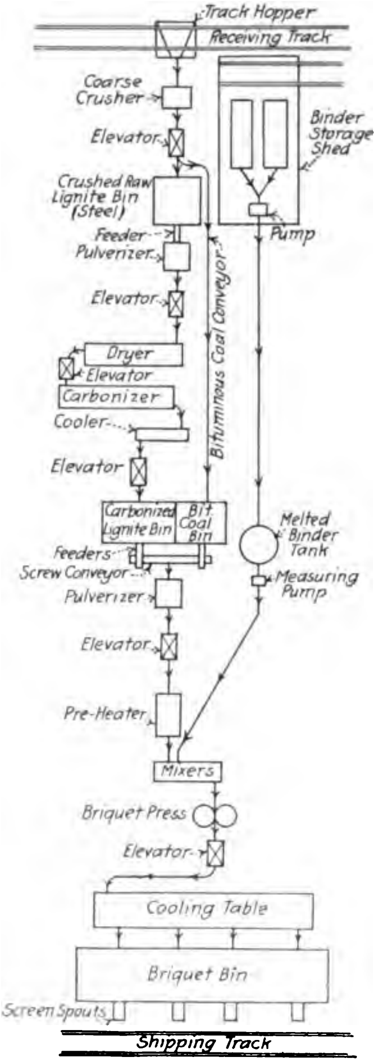

FIG. 62.—Flow Sheet No. 3.—Lignite partial carbonizing and briquetting plant, to use melted pitch or asphalt binder.

Lignite can be successfully briquetted so that the briquets will remain permanently hard and not disintegrate during combustion; in fact, they will improve with age, provided all the free moisture and part of the lighter volatiles are driven off before the material is briquetted, by partial carbonization or distillation of the raw material. Briquets made of partially carbonized lignite are superior in heating value to those made of entirely carbonized lignite; but entirely carbonized lignite can be briquetted with a binder so as to produce an entirely smokeless and odorless fuel during combustion, equal in heating value to and slightly freer-burning than Pennsylvanian anthracite. There are two methods that may be followed in the utilization of the lignites by briquetting. The plant to carry out the first by drying and partial carbonization, as shown in Fig. 62, calls for a considerably lower cost of plant, as compared with the complete by-product plant, and is recommended for smaller installations and in localities where there is a very small or no market locally for the gas obtained from complete carbonization of the lignite and a very distant market for the other by-products. In this plant (Fig. 62) all the by-products are allowed to go to waste, all the free moisture in the lignite is driven off, and from a trace to one-quarter of the volatile matter is expelled. Experiments have shown with lignites from Texas, Mississippi and the Dakotas, that it is necessary to expel some of the lighter volatiles in order to prevent the residue from further air-slacking and disintegrating the binder in the briquet. In this process the drying and partial carbonization are carried on in specially designed, indirect heat, rotary carbonizers, raw lignite being used for fuel. With lignites containing a low percentage of moisture, this drying and partial carbonization may be accomplished in one machine. When the lignite is high in moisture —running above 15 per cent—better results are obtained in first passing it through an ordinary dryer and then through the mechanical carbonizer or roaster.

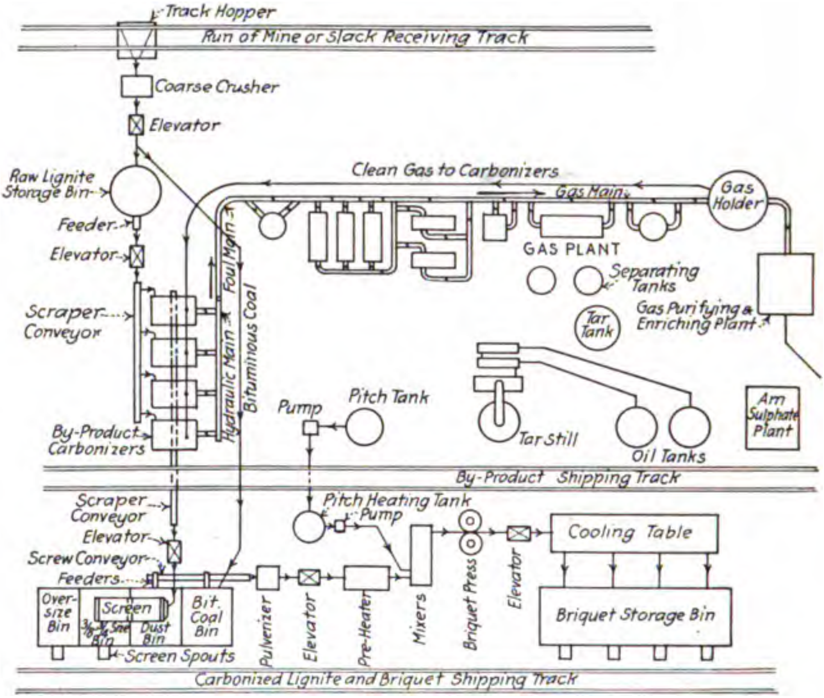

FIG. 63.—Flow-sheet of lignite by-product carbonizing and briquetting plant.

A by-product process is shown in Fig. 63. In order to adapt this process to American requirements, it was found that it would be necessary to develop and design a new type of carbonizing retort that would give the same gradual or progressive method of distillation as is being used in Europe; that is, passing the lignite from the temperature of the atmosphere slowly through the retort chambers, gradually increasing the heat as the material descends by gravity, until the lignite reaches the red hot part of the retort and completes the carbonization. The gases or by-products obtained during this gradual carbonization must be removed immediately after they are given off, so as to prevent cracking and fractionation, thereby reducing the quantity of pitch and oils, and increasing the quantity of gas and its heating value.

The following tables give average proximate analyses of different lignites, including the percentages and amounts of by-products that it is possible to recover from the different lignites of the country in a properly designed and equipped by-product carbonizing and briquet plant. The composition of the lignite from each particular deposit varies slightly. The lignites of the Pacific Coast are of higher grade than those of the

PROXIMATE ANALYSES OF AMERICAN LIGNITES

RAW LIGNITES

	Texas	North Dakota	Pacific Coast	Saskatchewan
Moisture, per cent	25.17	32.30	15.29	25.13
Volatile combustible, per cent	36.69	25.50	31.10	28.11
Fixed carbon, per cent	28.45	35.00	39.63	38.16
Ash, per cent	8.79	6.00	13.17	6.86
Sulphur, per cent	0.90	1.20	0.81	0.74
B.t.u	7,661	7,500	9,031	8,210

DRY BASIS

	Texas	North Dakota	Pacific Coast	Saskatchewan
Volatile combustible, per cent	50.48	47.60	37.1	38.5
Fixed carbon, per cent	37.81	41.43	47.0	52.0
Ash, per cent	11.71	11.09	15.9	9.5
Sulphur, per cent	0.90			
B.t.u	10,212	10,030	10,750	11,421

ULTIMATE ANALYSIS ON DRY BASIS

Carbon, per cent	57.06	59.55	63.09
Hydrogen, per cent	4.40	4.21	4.49
Oxygen, per cent	23.70	19.83	12.40
Nitrogen, per cent	1.53	1.11	1.02
Sulphur, per cent	0.64	4.21	3.10
Ash, per cent	12.67	11.09	15.90

AVERAGE APPROXIMATE PRODUCTS OBTAINED BY CARBONIZATION OF ONE TON (2000 LBS.) OF RAW LIGNITE

	Texas	North Dakota	Pacific Coast
Residue—carbonized lignite containing 4 to 6 per cent volatile, pounds	815	870	1,112
Tar and tar oils, water free, gallons	21	18	24
Gas, 325 to 380 B.t.u., cubic feet	8,200	8,000	9,000
Ammonium sulphate	18	16	20

FROM THE DISTILLATION OF TAR ARE OBTAINED THE FOLLOWING

Motor spirits, gallon	1.00	0.75	1.25
Gas oil, gallons	3.25	2.25	4.50
Fuel oil, gallons	9.75	8.50	11.25
Lignite pitch 150°F. melting-point, ring and ball test, pounds	65	60	65
Raw lignite required to produce one ton of carbonized lignite, pounds	5,000	5,000	3,600

Lignite, properly carbonized so as to recover the maximum amount of by-products, does not afford benzol and its homologues, or other hydrocarbon of the aromatic series, etc., in sufficient quantities to warrant the installation of additional apparatus for the recovery or separation of these products. No data are given as to what other chemicals and drugs can be obtained by hydrolysis, further distillation and fractionating, since they form the basis of a separate industry.

North Dakota and Texas fields, and the Colorado and Wyoming lignites are usually higher in ash but are otherwise of about the same nature and composition as those on the Pacific Coast.

BINDERS

The question of binders for the briquetting of fuels in America has been a subject upon which a great many seem to think the whole industry depends, when, as a matter of fact, good coal tar pitch, if properly handled and small quantities of it are used, and the briquets are made under a suitable pressure with the coal properly prepared, produces a first-class briquet practically for all parts of the country except that portion of the East which uses anthracite coal exclusively in domestic use. Asphalt is being produced in recent years in larger and constantly increasing quantities, being obtained principally from the distillation of asphalt-base crude petroleums, so that today this material is available at about the same cost as coal tar pitch, figuring on the cost of the binder per ton of briquets and not per ton of the binder. Asphaltum is a better binder than coal tar pitch for the reason that it contains no tar oils, it possesses a higher distillation-point than coal tar pitch, and it is practically smokeless and odorless during combustion. Briquets are today being manufactured in several plants using this material which are advertised as smokeless, although in a correct sense this is not so as they do produce a white steam-like oil vapor on ignition.

To those unfamiliar with the problem of briquetting, the question of binder always has appeared to be the stumbling block, inasmuch as many have seemed to think that a suitable binder would solve the whole problem. There have been a large number of patents granted, some so ridiculous that it is surprising that the Patent Office would issue them, the object in all cases being to produce a smokeless, odorless and waterproof binder or briquet that would be cheaper than coal tar pitch or asphaltum or its product.

A number of binders have, however, been developed and several plants are in operation in the United States which produce a smokeless and odorless briquet; but so far all the smokeless binders require the use of a baking or drying oven for the briquets, usually to evaporate the water which, as a rule, is the base of all these binders, carrying the different ingredients either in solution or suspension.

Among the binders that have given satisfactory results is molasses treated in various ways, some patented. Molasses in itself makes an excellent binder, and, when properly treated, is odorless and smokeless; but its price at the present time prevents its use for this purpose. Starch or dextrin pastes and an asphalt-base oil make a good binder. For anthracite coal there usually is required from 1 to 1½ per cent of flour, which must be converted into starch, and from 1 to 2 per cent of heavy asphalt-base oil. The construction of the plant to use this binder is simple, but it requires an oven for drying the briquets. The general objection to some of the processes which have been devised is that there is a considerable amount of water necessary to convert the flour into starch. But the process wherein flour is cooked with water, then mixed with oil to produce an emulsion, has been improved upon, so that flour now can be converted into starch by the use of very little water. The briquets made with flour and oil binder usually improve with time and on exposure to air, and this improvement seems to be due to the oxidation of the oil.

Hydrocarbon Binders.—In addition to asphalt, there are large deposits in the western part of the United States of hydrocarbon minerals such as gilsonite and elaterite, and others of allied nature, many of which are sticky, adhesive, have a satisfactory melting-point, and produce little or no smoke and no fumes during combustion. These materials probably make a better and more nearly smokeless binder than anything else obtainable among the hydrocarbon complexes. There is no difficulty in handling them, either in a liquid or pulverized state, and, on account of the location of their deposits, the establishment of briquetting plants is possible for the production of high-grade domestic fuel in many localities where more or less inferior coals are obtainable.

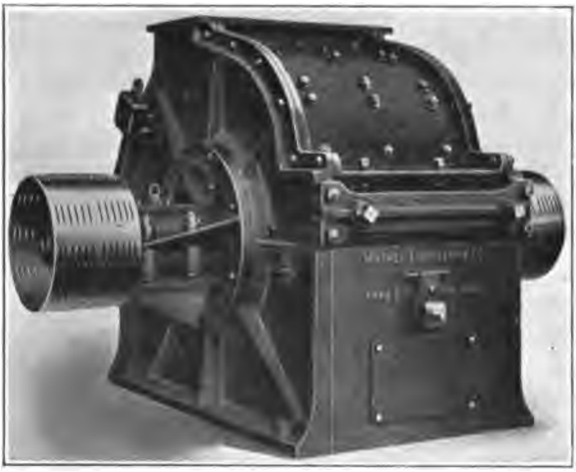

FIG. 64.—Briquette-plant coal-pulverizer.

Asphalt cut with alkalies or acids, so as to make it soluble in water, can be used and produces a fair briquet. However, it usually is advisable to bake or heat the briquet to expel water. The object of combining water with asphalt is to be able to distribute a small percentage of asphalt through a large amount of dust so as to cover each particle and use a less quantity. To use asphalt in this way adds to the cost of the plant, and the object for which it was first developed has in recent years been eliminated by improvements made in processes and mixers so that there is no difficulty in distributing evenly through the coal dust any percentage of binder it may be desired to use, and properly coat each particle of coal. Good briquets have been produced with as low as 1½ per cent of straight asphalt on certain coals. As a rule, for anthracite there is required about 5 per cent when the material is pulverized so as to pass a 14- to 16-mesh mining wire screen, and, of course, a large percentage of this is reduced to pass through a 100-mesh screen. The amount of any binder used depends entirely on the strength that the briquet must possess, considering the coal it is made from, in order to meet the requirements of the trade. No process of diluting asphalt or any other binder, in order to use a smaller percentage and spread it thoroughly through coal, will increase the binding quality of the binder *per se*.

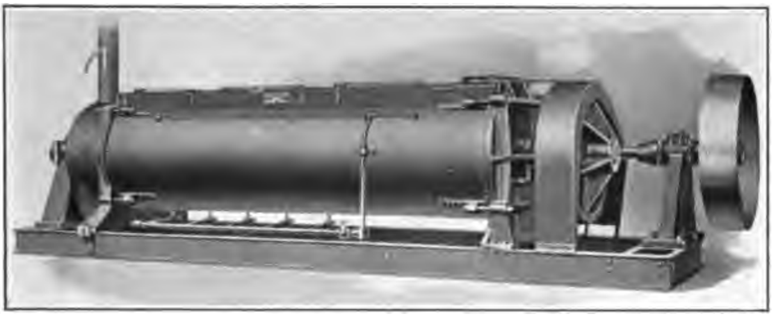

FIG. 65.—Steam-jacketted mixer and pug mill.

Oils.—Oils from coal tar, still containing a percentage of coal-tar pitch, mineral asphalt-base oils containing asphalt in solution, or other oils carrying some adhesive substance, all can be used as binders for coal dust. The thinner the binder, the more finely the dust must be pulverized, and the more thorough the mixing, pugging, squeezing or grinding together of the dust and such oils must be carried on in order to get a thorough amalgamation or mixing before delivery to the briquet press. If the oils do not possess any fairly quick hardening tendencies, the briquet must be subjected to a drying or baking process to expel or distil off the lighter volatile constituents of the oils which have no binding qualities in themselves, in order to make a hard briquet. The oil in this case acts only as a carrier for the pitch, asphalt or other substance that is the real binder, but the hardness of the briquet depends, as a rule, entirely on the amount of solid real binder ingredient the oil carries in solution or suspension which remains in the briquet after the oil which has no binding qualities evaporates or oxidizes and hardens.

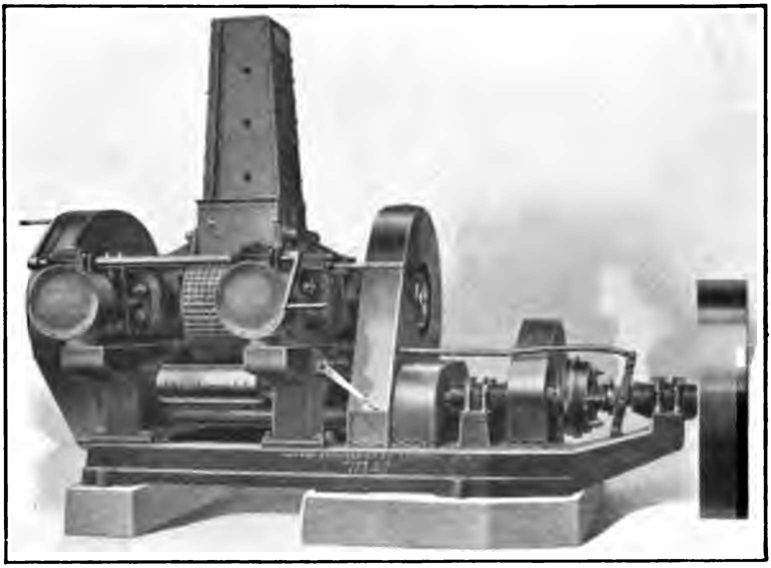

FIG. 66.—20-ton per hour briquette-press; 2¼ ounce briquettes; weight, 42,000 pounds.

A European process, extensively tried in the United States in recent years, which consists in using either a tar, gas, mineral or waste combustible oil that is incapable in itself of acting as a binder for solid fuel, claiming to produce a hard briquet by thorough mechanical kneading and crushing of the coal with the oil, and making a paste in order to get a homogeneous mixture, has proved to be a commercial failure. The reason is that, in order to make a hard briquet, this oil must harden by slow air oxidation. There the process has been abandoned, and oil residuum asphalt compound of about 140 to 160°F. melting-point is now used.

Oils having no binding qualities in themselves can be used only to briquet coals that contain a considerable quantity of soluble pitches or bitumens. These coals, when finely ground with such oils, especially if heat is applied, are acted upon by the oil, which dissolves or softens the pitches or bitumens in the coals so as to make them plastic or sticky and thus capable of holding the particles of coal together when pressed. Then, if some of this non-binding oil can be removed from the briquet by distillation or baking or slow air drying and oxidation, the product will be hard and stand ordinary transportation and handling. Coals in America containing a sufficient quantity of easily soluble pitch or bitumen are not plentiful, usually possess coking qualities so that the slack can be converted into coke, and, if not of a coking nature, as a rule do not air slack or produce large breakage in handling. When oils such as those described are used to briquet anthracite, charcoal, coke breeze or other fuels containing little or no volatile matter, regardless of how they are mixed or incorporated with such fuels, they do not produce satisfactory commercial results. The hardness of the briquet depends on slow oxidation or hardening of the oil. Solid oil or grease has no

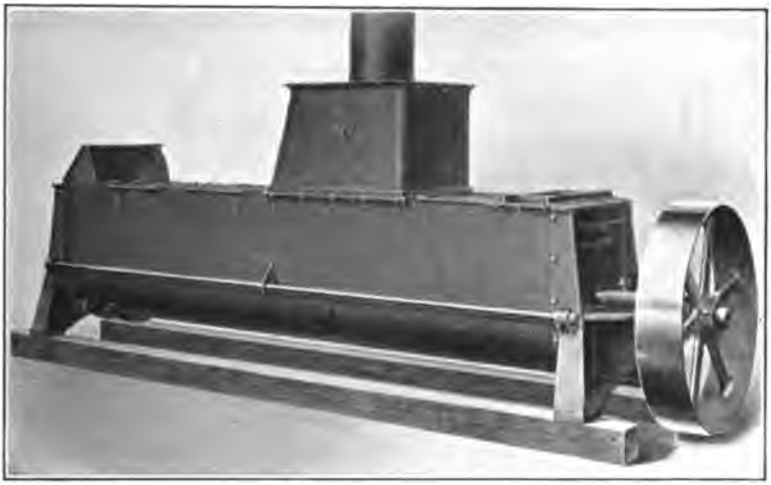

FIG. 67.—Finishing mixer.

binding qualities. The various processes of solidifying petroleum or other oils do not add to their binding qualities, and these oils are not suitable for briquetting coal.

On the American continent, practically the only coals that call for briquetting are those that are friable and have poor or no coking qualities. In order to briquet them so as to make a high-grade commercial product, the binder must have adhesive or binding qualities so as to make briquets from any of these coals that will stand as much handling as prepared sizes of anthracite and produce less breakage, be odorless, remain hard in the fire, be waterproof and practically smokeless.

Sulphite Pitch.—Sulphite pitch of 30°Bé. or heavier, a by-product from sulphite wood-pulp mills, makes an excellent binder, and it is also used extensively under the trade-names of "glutrin" and "binderine" in foundries for core binder in place of molasses and flour. "Lignone" and "cell pitch" are similar products. When dry it makes a hard carbon that does not soften on heating. The objection to this binder for briquetting purposes has been its hygroscopicity when dried out in the briquet, causing the briquet to absorb a large amount of water and soften. To overcome this, several processes have been patented for waterproofing sulphite pitch, all of which are based on using some waterproof material such as asphaltum, coal-tar pitch or oils mixed about one part of oil to four to five of sulphite pitch, the mixture being made either in the mixer or binder preparing tank. The briquets in all cases must be baked or

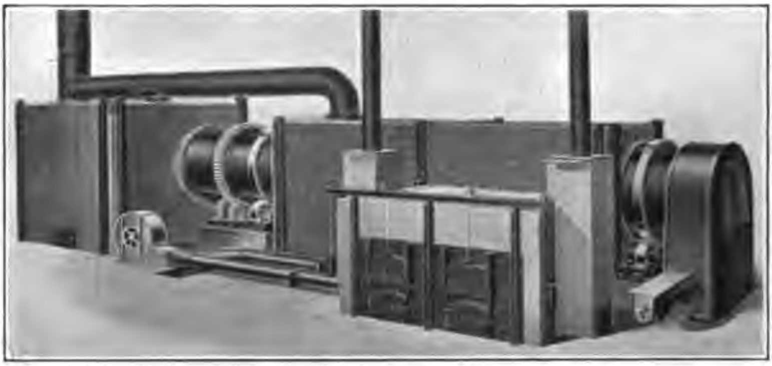

Fig. 68.—Lignite rotary dryer and partial carbonizer, direct or indirect heat dryer.

dried and raised to a temperature which is sufficient to expel the water contained in the pitch.

In using sulphite pitch as the binder for certain bituminous and other coals that contain oily, tarry volatile matter which begins to distil freely at, say, not above 550°F., first-class, hard and waterproof briquets that will not fuse or soften in the fire can be made without the introduction of any waterproofing compound. Most coals of this character usually swell on ignition; and to eliminate or reduce that tendency and prevent the checking of the briquets during combustion, the raw material first should be prepared properly and put through a high temperature dryer to expel all moisture and possibly some of the lighter volatile matter of the coal. The briquet would be further improved and made more smokeless if passed through a heat treatment in an oven, so as to drive off the water of the sulphite pitch, and set the sulphite proper to a solid carbon.

Fig. 69.—Steam-heated rotary dryer or preheater.

Sodium Silicate.—Considerable experimental work has been devoted to the use of sodium silicate as a binder. While it adds a small percentage of mineral matter to the coal, and lowers the fusion point of the ash, it has some good qualities and may in time be developed into a binder of considerable value. The difficulty lies in waterproofing the product.

There are numerous inventors still working on binders, some of whom have produced briquets of the highest quality, extremely hard, waterproof and all that can be desired, and, as the field is so large, there is still room for improvements in this direction; but the day of revolutionizing the industry or creating a bonanza by the discovery of some new binder is past. The cost of binder per ton of briquets must be taken into consideration, as well as the plant and equipment necessary to handle it properly. While the general opinion is that the cost of binder should be below about $1.00 per ton of briquets, its cost, however, should not be taken as the only element entering into the manufacture of briquets. Cost of coal with which the briquets will compete and the quality of the briquets in comparison with the best available fuels are really the determining factors of what the minimum price of the binder may be in order to be commercially available.

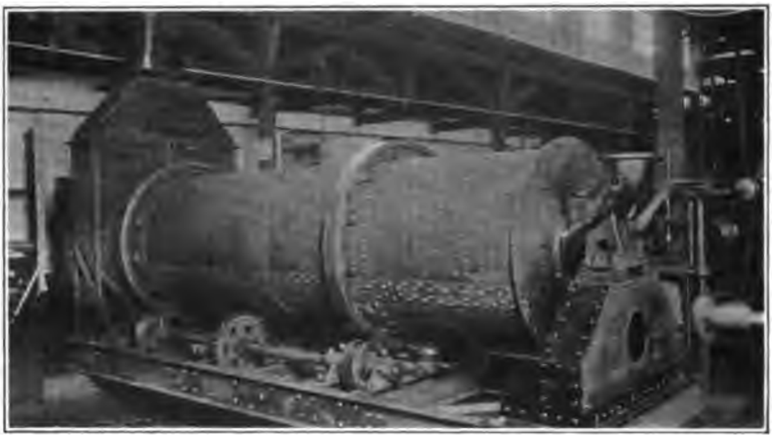

Fig. 70.—An improved design of rotary steam dryer and preheater, superseding Fig. 69.

COST OF PLANT

The cost of a complete briquetting plant, for reasons explained before, will vary greatly, depending on the coal to be briquetted, the kind of product desired and the purpose for which it is intended. The following figures are for different capacities of plants of the single-unit type, erected east of the Missouri River, based on material and labor costs of 1921:—

	6 tons per hour	10 tons per hour	20 tons per hour
Straight pitch or asphaltum binder plant	$62,800	$101,000	$140,000
Smokeless binder briquet plant	82,850	137,450	186,950
Lignite briquetting and partial carbonizing plant	....	185,000	260,000

The cost of buildings is based on heavy wood-frame construction, and the prices include the complete plant from one end to the other, so as to be entirely automatic, beginning with the dumping of the cars containing the dust and raw material up to spouting the finished product into cars and wagons. It includes the cost of moderate sized bins for the storage of raw material as well as briquets, and also includes a complete power plant and a small generating unit for lights. The prices set down are only general and will vary with local conditions, local cost of material and labor for the erection of the buildings, and freight rates on machinery from the shops. For instance, a small 5-ton per hour plant has been erected for considerably less than the figures given, and a plant on the Pacific Coast, briquetting bituminous coal, with a capacity of approximately 30 tons an hour of 7-oz. briquets, cost $225,000.00 in 1912.

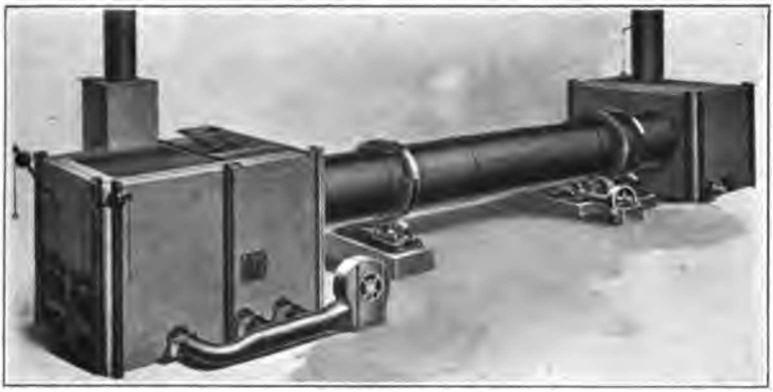

FIG. 71.—Direct-heat rotary dryer, Dutch-oven furnace type.

The cost of a lignite-carbonizing, by-product and briquet plant is not given for the reason that the cost of such a plant varies so greatly in output and type of retorts, gas scrubbing, chemical and by-product plant, and depends, moreover, on the amount of moisture the lignite contains and the ultimate analysis, all of which items have to be considered carefully and the proper equipment specified. The minimum size plant of this description should have a capacity of at least 150 tons to 200 tons of carbonized lignite and carbonized lignite briquets per day. The carbonizing and by-product part of such plants must be operated continuously 24 hr. per day, but the briquet plant can be large enough to be run only during the day shift.

In conclusion, it will be clear from the foregoing that there are no unsolved fundamental problems in briquetting practically any kind of material, especially in the field of fuel. Inventions and improvements will be made in the future, as in the past, so that the manufacture of briquets will be improved, simplified and cheapened; but there is nothing that stands in the way of the design and construction of a briquetting plant to briquet any kind of coal, if this work is entrusted to engineers who have had experience in this particular line, as in any other industry that requires special, properly designed machinery and its systematic arrangement and installation.

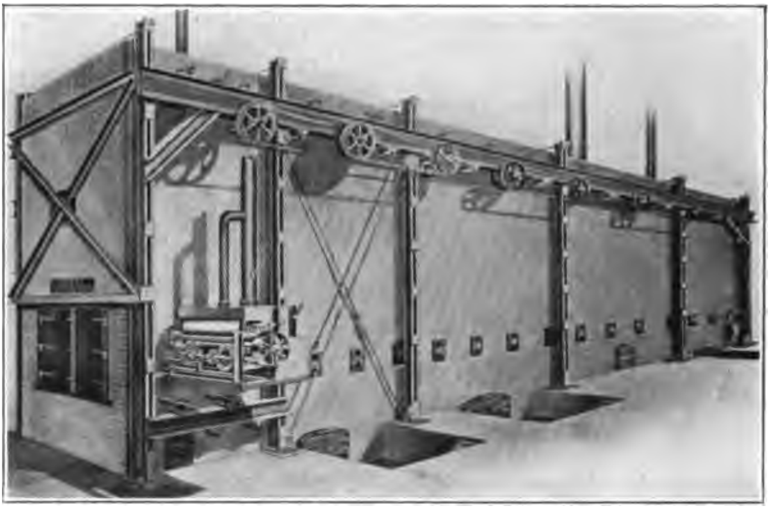

Fig. 72.—Briquette baking or drying oven.

The illustrations show the important special machinery used in the equipment of modern briquetting plants.

COSTS OF MANUFACTURE

The cost of manufacturing briquets varies greatly in different localities, depending on the costs of raw material, labor, binder delivered, and kind of coal briquetted. The following estimated costs of manufacture for different fuels in different parts of the country are given as examples as to what the product costs, and for each individual installation the cost of the different elements mentioned above must be taken into consideration. Most of the estimates given below have been obtained from plants in operation.

COST OF MANUFACTURING BRIQUETS FROM ANTHRACITE MIXED WITH 5 PER CENT BITUMINOUS COAL, OR BITUMINOUS COAL ALONE, OR MIXED WITH OTHER FUELS, USING COAL TAR PITCH OR ASPHALTUM BINDER

(July, 1921)

ANNUAL PRODUCTION 80,000 tons (2,000 lbs.) of briquets.

BASIS OF OPERATION, average output 19 tons per hour of about 2⅜ oz. briquets, plant running 6 months, Oct. 1, to Apr. 1, 140 days, 24 hours per day, and about 120 days 10-hour day shifts for balance of year; plant running 260 days per year, allowing balance of year for Sundays, holidays, annual overhauling of plant, vacations and other possible delays; total running time, 4400 hours, or 400 shifts, operating crew employed 425 shifts per year.

RAW MATERIAL

Anthracite dust or culm per ton of 2,240 lb. at briquet plant	$1.00		
10 per cent of water in dust	.10		
Cost per gross ton of dry dust	$1.10		
71,500 net tons = 63,800 gross tons of dry dust @ $1.10		$70,000.00	
4,000 tons of coking bituminous coal (5%) at $6.00 per net ton		24,000.00	
5,000 tons of coal-tar pitch or asphaltum binder at $18.00 per ton, delivered		90,000.00	
Total cost of raw materials per annum			$184,000.00
Cost per ton of briquets shipped	$2.30		

FUEL FOR PLANT, SUPPLIES, & BREAKAGE

Consisting of briquets, screenings from anthracite dust and bituminous coal			
3,500 tons for boiler @ $4.00		$14,000.00	
Oil, waste, packing, lamps & other supplies		1,000.00	
Re-briqueting dust caused by breakage and abrasion of briquets in plant and bins, 5 per cent, 4,000 tons at $1.00 per ton		4,000.00	
Total cost of fuel, supplies & breakage per annum			$ 19,000.00
Cost per ton of briquets shipped	$0.24		

Labor

425—10- & 12-hour shifts (285 day shifts)		
1 Superintendent and briquet expert, per annum	$ 3,000.00	
1 Assistant superintendent at nights, per annum	2,000.00	
1 Mechanic and engineer, 285 days @ $5.00	1,425.00	
1 Steam engineer, 425 shifts @ $5.00	2,125.00	
1 Boiler fireman, 425 shifts @ $4.00	1,700.00	
1 Boiler fireman's helper, 425 shifts @ $3.25	1,381.00	
4 Yard and plant laborers, 285 shifts @ $3.00 each	3,420.00	
1 Oiler and general handy man, 425 shifts @ $3.50	1,488.00	
1 Plant cleaner and helper, 285 shifts @ $3.00	855.00	
1 Dust bin and preheater man, 425 shifts @ $3.50	1,488.00	
1 Mixer and binder man, 425 shifts @ $4.00	1,700.00	
1 Press, feeder and pulverizer man, 425 shifts @ $3.50	1,488.00	
1 Binder heater and tank man, 285 shifts @ $3.50	998.00	
1 Yard foreman, 285 shifts @ $4.00	1,140.00	
Employees liability insurance	1,500.00	
Total labor cost per annum		$ 25,708.00
Cost per ton of briquets shipped $0.32		
Assistant to salesmen, instructor and expert fireman, complaint man, etc., @ 5c per ton		4,000.00

Overhead & Fixed Charges

General office manager		$ 3,600.00
Watchman, 365 nights, 52 Sundays, 8 holidays, total 425 shifts @ $3.00	1,275.00	
1 Clerk, stenographer and timekeeper	1,800.00	
1 Office boy	960.00	
Telephone, telegraph, stationery, postage, etc.	1,000.00	
Rent or interest on plant site investment	1,000.00	
Taxes, local and income	2,250.00	
Insurance (wood-frame buildings)	3,000.00	
Repairs and renewals of wearing parts of machinery	7,500.00	
Repairs, upkeep and painting of buildings	2,500.00	
Depreciation or obsolescence of plant and bldgs.	12,000.00	
Contingencies and unforeseen expenses, first year	4,000.00	
Total overhead per annum		$ 40,885.00
Cost per ton of briquets shipped $0.51		
Total cost of operation per annum		$273,593.00
Total cost per ton of briquets, F. O. B. cars at plant		3.42

Estimated Cost of Manufacturing Lignite Briquets
Type "C-3" Plant, Without Recovery of By-products.
Plant Located at Mine

(June, 1919)

Pacific Coast lignite of the following analysis:

Moisture 18 per cent., fixed carbon 45 per cent., volatile combustible matter 32 per cent, and ash 8 per cent.

Lignite dried and partially carbonized in rotary carbonizers.

Capacity of plants, 18 to 20 tons of briquets per hour, depending on size of briquets.

Minimum capacity, running two 12-hr. shifts for 235 days per year, producing 90,000 tons of briquets.

Loss in drying of raw lignite, 20 per cent.

Material and Supplies

107,000 tons (2,000 lb.) raw lignite	@$ 2.85 per ton	$304,750.00	
6,750 tons asphalt	@ 16.00 per ton	108,000.00	
4,500 tons coking bituminous coal	@ 10.00 per ton	45,000.00	
4,5000 tons lignite for fuel for carbonizers and boilers	@ 2.90 per ton	4,050.00	
Oil, supplies, lights, etc.		800.00	
Total cost of material and supplies		$471,600.00	
Cost of material and supplies per ton of briquets			$5.24

Labor for Two Shifts per Day

1 Plant superintendent			$3,000.00	
1 Assistant superintendent per annum			2,100.00	
1 Man, crusher	250 days	@ $4.00 per day	1,000.00	
2 Men, bins and cooling table	250 days	@ 4.00 per day	2,000.00	
2 Men, heating binder	250 days	@ 4.00 per day	2,000.00	
2 Men, firing carbonizers	250 days	@ 4.50 per day	2,250.00	
2 Men, preheater and mixer	250 days	@ 4.50 per day	2,250.00	
2 Men, firing boilers	250 days	@ 5.00 per day	2,500.00	
2 Men, press, pulverizer, feeders, etc.	250 days	@ 5.00 per day	2,500.00	
2 Men, plant laborers and oilers	250 days	@ 4.50 per day	2,250.00	
3 Men, unloading and loading cars	250 days	@ 4.00 per day	3,000.00	
1 Engineer and mechanic	300 days	@ 6.00 per day	1,800.00	
1 Yard foreman	300 days	@ 5.00 per day	1,500.00	
Total labor cost per annum			$28,150.00	
Labor cost per ton of briquets				$0.31
Rebriquetting breakage, etc., per ton of briquets				0.12
Carried			$5.67	

Fixed Charges and Overhead Expenses

Salary and expenses of one salesman per annum	$ 5,000.00	
Salary of manager per annum	3,500.00	
Timekeeper and clerk per annum	1,500.00	
Telephone, telegraph, stationery, postage, etc.	1,000.00	
Repairs and renewals to plant per annum	7,500.00	
Depreciation per annum	10,000.00	
Insurance per annum	1,500.00	
Taxes per annum	800.00	
Unforeseen contingencies, accidents, etc.	3,000.00	
Total fixed charges per annum	$33,800.00	
Fixed charges per ton of briquets		$0.38
Cost per ton of briquets f.o.b. cars plant		$6.05

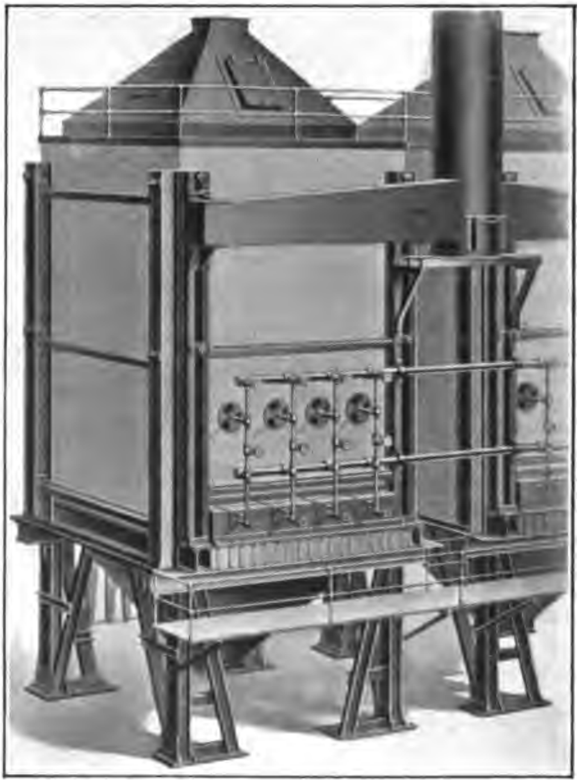

FIG. 73.—Lignite carbonizer or by-product retort, firing side.

Estimated Cost of Manufacturing Carbonized Lignite and By-products on Type "C-3" By-product and Briquet Plant

(As of June, 1915)

Operating on Pacific Coast lignites of the following analysis:

Moisture 15 per cent, fixed carbon 45 per cent, volatile combustible matter 32 per cent, and ash 8 per cent.

Capacity, 250 tons of raw lignite per 24 hr.; 90,000 tons per annum.

Carbonizing and by-product plant running 24 hr. per day; briquetting plant, 10 hr. per day.

To produce 1 ton of carbonized lignite there will be required 1.8 tons of raw lignite.

Cost of Material and Supplies

Lignite slack, 90,000 tons @ 85 cts. per ton (2,000 lb.)	$ 76,500.00
Lignite for tar-distilling plant to distil 15 per cent tar, 1,000 tons @ $1.00	1,000.00
Bituminous coal for briquetting purposes, 2,300 tons @ $3.50	8,050.00
Pitch for briquetting, 2,300 tons @ $10.00	23,000.00
Fuel for boilers, which will be either excess gas or oil recovered from lignite. Estimate based on oil, 17,700 bbl. @ 60 cts.	10,620.00
Lubricating oil and waste	1,000.00
	$120,170.00

Labor per Annum

As itemized below	39,660.00

Fixed Charges and Overhead Expenses

As itemized below	52,200.00

Rebriquetting

Breakage, abrasion, dust, etc., from briquets @ 6 cts. per ton of briquets	2,400.00
Total expenses per annum	$214,430.00

Yield of Products per Annum

12,500 tons of lump carbonized lignite suitable for domestic use, gas producers, etc., @ $3.50 per ton	$ 40,000.00
2,000,000 lb. ammonium sulphate @ 3½ cts. per pound	70,000.00
2,300 tons of pitch used in the briquetting plant @ $10.00	23,000.00
29,000 bbl. fuel oil @ 60 cts. per barrel	17,400.00
41,000 tons of briquets @ $3.50	143,500.00
Total income	$293,900.00
Fuel value of gas as given below	27,000.00
Total estimated income per annum	$320,900.00

Gas.—One ton of this lignite will yield 9,000 cu. ft. of gas. There will be consumed in the retorts and the by-product equipment 60 per cent of this gas, leaving an excess of 40 per cent, or 3,600 cu. ft. per ton. From 90,000 tons there will be obtained 324,000,000 cu. ft. of gas. This gas, after passing through the condensation and washing process, will contain 15 per cent of CO_2, a trace of H_2S and cyanogen. Its heating value is from 390 B.t.u. to 400 B.t.u. This excess gas is all based on oil being used for fuel under boilers. If this excess gas is used for this purpose, assuming that this gas is only valued at its fuel value in comparison with lignite at the mine, figuring the screened lump lignite at $1.50 per ton, including the labor of firing, the value of this gas would be 6 cts. per 1,000 cu. ft.; and assuming, to be on the safe side, that only 300,000,000 cu. ft. of this gas are disposed of, if not used under the boilers in place of oil, the value of this gas for fuel purposes is $27,000.00. If this gas is used for illuminating and other commercial purposes, the heat value must be increased to from 500 B.t.u. to 550 B.t.u. This may be done by using the lignite tar oils, and there will be required about 10 lb. of oil for every 1,000 cu. ft., and then extracting the CO_2. It is safe to assume that there will be available approximately 224,000,000 cu. ft. of the enriched gas per annum. The amount of gas oil produced is more than sufficient for enriching the above amount

FIG. 74.—Briquette cooling table

FIG. 75.—2¼ oz. briquette, ⅝ original size, semi-anthracite.

of gas. This gas on the Pacific Coast should have a value of approximately 20 cts. per 1,000 cu. ft., or $44,800.00.

Ammonia.—This lignite, on a dry basis, contains 1.42 per cent of nitrogen; raw lignite, 1.17 per cent. One ton therefore contains 23.4 lb. of nitrogen, Assuming that only 20 per cent or 4.68 lb. of this nitrogen will be converted into NH_3, which is equivalent to 5.7 lb. of NH_3 or 22.8 lb. of $(NH_4)_2SO_4$, deducting the loss of 0.8 lb. of NH_3 per ton of raw lignite, there will be obtained, say, 22 lb. of ammonium sulphate per ton. Therefore, 90,000 tons will produce approximately 2,000,000 lb. of ammonium sulphate.

Tar.—As there will be obtained from 1 ton of raw lignite 150 lb. of tar, or a total per annum of 6,750 tons, by fractional distillation this tar will yield the following: 20 per cent. gas oil, 43 per cent fuel oil, and 35 per cent pitch, with a total loss of 2 per cent.

LABOR

2 Men unloading cars	@ $2.00 =	$4.00, 300 days =	$ 1,200.00
1 Man at crusher	@ 2.50 =	2.50, 300 days =	750.00
4 Men charging and discharging retorts	@ 2.25 =	9.00, 365 days =	3,285.00
2 Foremen		@ $1,200.00 =	2,400.00
2 Men at furnace	@ 2.00 =	4.00, 365 days =	1,460.00
2 Men at gas plant	@ 3.00 =	6.00, 365 days =	2,190.00
2 Helpers at gas plant	@ 2.00 =	4.00, 365 days =	1,460.00
2 Men at NH_3 plant	@ 3.00 =	6.00, 365 days =	2,190.00
1 Helper at NH_3 plant	@ 2.00 =	2.00, 365 days =	730.00
1 Man at tar plant	@ 3.00 =	3.00, 300 days =	900.00
1 Helper at tar plant	@ 2.00 =	2.00, 300 days =	600.00
1 Foreman at briquetting plant			$1,2000.00
3 Assistants	@ 2.50 =	7.50, 300 days =	2,250.00
1 Man at briquet bin	@ 2.50 =	2.50, 300 days =	750.00
2 Firemen at boilers	@ 3.00 =	6.00, 365 days =	2,190.00
2 Helpers at boilers	@ 2.00 =	4.00, 365 days =	1,460.00
1 Mechanic	@ 4.50 =	4.50, 300 days =	1,350.00
1 Helper	@ 4.00 =	4.00, 300 days =	1,200.00
3 Laborers in yard	@ 2.00 =	6.00, 300 days =	1,800.00
1 Yard foreman	@ 3.00 =	3.00, 300 days =	900.00
1 Watchman	@ 3.00 =	3.00, 365 nights =	1,095.00
1 Chief engineer			1,800.00
1 Assistant			1,200.00
1 Bookkeeper in charge of office			1,200.00
1 Timekeeper and clerk			1,000.00
1 Man in laboratory			900.00
1 Superintendent			3,000.00
			$39,660.00

FIXED CHARGES AND OVERHEAD EXPENSES

Depreciation:				
Carbonizers and boilers	10 per cent	$132,000	$13,200.00	
Briquetting plant	6 per cent	43,000	2,500.00	
Gas, ammonia and tar-distillation and pumping plants	5 per cent	74,000	3,700.00	
Buildings	2 per cent	42,000	800.00	
				$20,200.00
Salary and expenses of one salesman per annum				4,000.00
Salary and expenses of one manager per annum				5,000.00
Repairs and renewals to plant per annum				16,000.00
Insurance (fire and employer's liability)				2,000.00
Taxes				2,000.00
Unforeseen contingencies and accidents				2,000.00
Telephone, telegraph, stationery, postage, etc				1,000.00
				$52,000.00

CHAPTER V

AN ECONOMIC REVIEW OF COAL PREPARATION AND THE UTILIZATION OF COAL ON A MULTIPLE-PRODUCT BASIS*

By

F. Parkman Coffin†

The efficient utilization of our fuel resources is a subject of constantly increasing importance. The United States and Canada have the greatest coal reserves of all countries; the summary in Table XXV shows that together these reserves amount to some 5.6 trillion tons, while the total known reserve for the whole world is only a little more than eight trillion tons, including coal of all ranks and grades.

Prior to the entry of the United States into the World War in 1917, few people manifested more than an academic interest in the conservation of our fuel resources. With the rapid industrial growth of the countries, both the United States and Canada have become more and more dependent on the coal supply for the very existence of their civilization. The development of waterpower has advanced fairly rapidly in Canada, but in the United States it has been discouraged by the lack of a constructive economic policy on the part of the government and by the misguided activities of advocates of "conservation." This has resulted in the "conservation" of our undeveloped waterpowers, by letting the water run to waste, at the expense of our fuel resources.

The effect of this policy has been aggravated by the fact that the art of generating and distributing hydro-electric power has been perfected far in advance of the more complex art of generating heat and power from fuel by efficient methods. Hydro-electric power may be developed with an efficiency of 80 to 90 per cent.

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* In this Chapter and the three following ones, the author reviews new methods applicable to the generation of power, and discusses their further application to industrial heating, together with the recovery and utilization of by-products.

† Research Laboratory, General Electric Co., Schenectady, N. Y.

TABLE XXV.—COAL RESOURCES OF THE UNITED STATES AND CANADA

Rank of coal	Estimate of the original coal in millions of tons					Production to end of 1914
	Anthracite and semi-anthracite	Semi-bituminous	Bituminous	Sub-bituminous	Lignite	
Fuel ratio (fixed carbon to vol. matter)	60 to 6	7 to 3	3 and less	3 and less	3 and less	(Total U.S.) 10,358
United States:*						
Eastern province	21,150	48,637	503,012	....	....	7,777
Interior province	400	1,226	528,273	....	....	2,015
Gulf province	......	......	....	....	23,090	10
Northern great plains	......	......	45,553	284,548	964,424	237
Rocky Mountains province	503	......	354,640	713,283	....	205
Pacific Coast province	......	......	11,439	53,459	....	115
Total, U. S.†	22,053	49,863	1,442,917	987,514	1,051,290	(Total coal)† 3,538,554
Alaska‡ (known coal fields)	2,130	1,496	17	4,063	13,875	21,581
Between 3,000 and 6,000 ft. of surface in Rocky Mountains						666,000
Canada:§						
Maritime provinces	......	......	10,857			
Ontario and Manitoba	......	......	....	....	204	
Saskatchewan and Alberta	846	......	217,918	932,053	94,898	
British Columbia	......	......	77,923	....	5,715	
Northern territories	......	......	6,600	....	10,440	
Total, Canada	846	......	313,573	932,053	111,246	1,357,718
North America (north of Mexico)	25,059	51,359	1,456,507	1,923,630	1,176,411	5,583,853

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* M. R. CAMPBELL, *U. S. Geological Survey, Prof. Paper* **100–A**, 1917. Also *Gen. Elec. Rev.*, Sept., **1918**, 617.

† Estimated supply within 3,000 ft. of surface.

‡ Est. by U. S. Geol. Survey, 1912, for coal fields actually explored, only. Consult *Gen. Elec. Rev.*, July, **1919**, 526.

§ A. V. WHITE, "Fuel Problem of Canada," *Gen. Elec. Rev.*, June, **1919**, 470.

The cheapness of fuel in America, in past years, has not offered any incentive to force us to improve upon the wasteful methods by which we have been utilizing our coal, petroleum and natural gas. The art of utilizing fuel for generating heat and power has been advancing slowly during the past century. Since the introduction of the steam turbine, in 1903, the efficiency of large power stations has been doubled and it is now possible to convert the thermal energy in coal into electrical energy with an efficiency of about 19 per cent. This, however, is possible only with the most modern equipment, both in the way of the main units and auxiliaries, and when the station is operating with a good load factor. Many obsolete and isolated plants are operating with an efficiency of less than one-third of this figure, and there is a big margin left for improvement even with the best available methods. Speaking broadly, the art has not kept pace with the rapid developments in the field of electrical engineering, or with the rate of increase in the consumption of fuel required to support modern industry and transportation.

During recent years there has been a considerable concentration of industries, and an increasing congestion of transportation facilities, in a zone extending from eastern Massachusetts along the Atlantic seaboard to Washington and for about 150 miles inland. The fuel consumption of the railways alone, in this zone, is about 12 per cent of the fuel consumed on all the railways in the country. The density of the power consumption has created much interest in the possibilities for coordinating the supply of electric power in this zone by gradually developing an interconnected network of transmission systems. The power would be generated in large modern central stations located with due regard to economical fuel supply and condensing water. The waterpowers of this zone would also be developed but would supply a minor proportion of the power, owing to their limited capacity. They can be utilized most effectively by storing water for carrying peak loads.

The waterpower resources of the United States and Canada are summarized in Table XXVI. These figures do not take account of storage possibilities for the reason that the utilization of storage sites is largely dependent upon local engineering and economic considerations. Storage reservoirs will help bring the average annual power nearer to the estimated maximum. In many cases the building of storage reservoirs will render prac-

TABLE XXVI.—WATERPOWER RESOURCES OF THE UNITED STATES AND CANADA

Estimated Maximum Horsepower without Storage (U. S.)[*]

District	Potential horsepower	Developed horsepower	Per cent developed of maximum for district
New England	1,951.000	1,506,500	77.2
Atlantic States	9,348,000	2,952,850	31.6
Central States	7,360,000	2,699,200	36.7
Mountain States	14,851,000	1,113,990	7.5
Pacific States	25,850,000	1,551,000	6.6
Total for U. S.	59,360,000	9,823,540	16.6
Low-water horsepower[‡‡‡]	30,000,000		

Estimated 24-hour Low-water Horsepower (Canada)[††]

			Per cent developed of minimum for district
Canada			
Maritime Provinces	453,000	45,500	10.0
Quebec	6,000,000	900,000	15.0
Ontario	6,000,000	1,000,000	16.7
Central Provinces	3,400,000	121,000	2.8
British Columbia	3,000,000	300,000	10.0
Northern Territories	No data	13,000	12.6
Total for Canada	18,853,000	2,379,500	....

[*] *Electrical World*, March 20th, **1920**, 654. Based on estimates made by the U. S. Forest Service, 1912, and by the U. S. Geol. Survey, 1915, and revised by the *Electrical World* as of January 1, **1920**.

[††] A. V. White, *Gen. Elec. Rev.*, June, **1919**, 467. (Statistics of Maximum h.p. for Canada and not available to the author.)

[‡‡‡] According to the U. S. Forest Service estimate of 1912, the maximum figures for the U. S. may be reduced by about one-half to obtain the low-water horsepower for comparison with the figures for the potential low-water horsepower of Canada.

ticable the installation of more generating capacity for carrying peak loads. This is especially true in the case of the smaller waterpowers, some of which might not otherwise be developed at all.

The Relative Fields for Waterpower and Fuel.—Philip Torchio summarizes the rôle of waterpower and coal in super-power systems, in his contribution to the symposium following W. S. Murray's paper, on the economical supply of electric power in the proposed zone.* He states that a review of the resources and consumption of coal and the availability of potential waterpowers in the United States shows that:

"1. The Western States (Mountain and Pacific) have resources in both coal and waterpowers to meet indefinitely all their heat and power requirements from either source of supply; the potential waterpowers alone being large enough to supply over six times all heat and power requirements of 1915.

"2. The other States, with corresponding heat and power requirements 40 times greater than the Western States, have actually smaller resources in coal and potential waterpowers, the latter capable of supplying only 8 per cent of their total heat and power requirements. It follows that these States must indefinitely, so far as present human knowledge can foresee, depend upon the use of coal to supply the bulk of these needs.

"3. These States, comparatively so deficient in waterpowers, consumed in 1915, 528,000,000 tons of coal, about one-half for generating power and one-half for generating heat. In utilizing coal, they generated power with an average efficiency of 5 per cent, while they generated heat with an average efficiency of 50 per cent.

"With present methods of generating power in large, modern central stations, the efficiency from coal has been raised to 19 per cent. If all the power had been so generated, the coal saving would have amounted to 185,000,000 tons and the railroads relieved of two-thirds of this kind of freight.

"4. As the investment cost of a steam plant is only about one-third or one-quarter that of a waterpower development, with its transmission connections and steam reserve, and as all other items of investment for the electrification of industrial plants would be the same with power generated either by steam or water-falls, it follows that every dollar invested in modern steam plants will make available several times more power for the industries than a dollar invested in hydro-electric plants.

"5. The offset for the greater overhead charges of hydro-electric power is the saving in coal. The value of this saving will

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* *J. Am. Inst. Elec. Eng.*, March, **1920**, 219 and 315.

be more or less, according to whether the power is used more or fewer hours every day of the year, and according to the unit price of coal.

"Under American conditions, the value of coal saving derived from the use of water power is usually smaller than the difference in overhead charges between steam plants and hydro-plants, except in cases where the power is used continuously every hour of the year, or where the development is connected to a large steam power system which will absorb the entire possible output.

"6. With certain industries, like electro-chemical processes and the refining of metals, using immense amounts of power continuously, the net cost of hydro-electric power may be considerably less than steam power. The more continuous waterpowers, and those without regulable daily storage, can be most advantageously utilized to intensify the development of these industries which can prosper and render their full benefit to the Nation only under conditions of mass production and most favorable cost of power.

"7. The harassing experiences of coal famines have repeatedly brought forth pressure that immediate efforts be directed to the development of the potential waterpowers of the country. While, from the general viewpoint of conserving the national coal resources, the proposition deserves most favorable consideration, it is questionable whether quicker and greater results can not be obtained by concentrating the effort upon improving and changing wasteful methods of utilizing coal. Modern methods for generating power by steam should be coordinated, and any policy for waterpower development, which will involve the diversion of the few but most economical large commercial loads, should be avoided. A policy of substitution of waterpower will involve duplication of plants and relegating the steam plants to supply the larger in aggregate but less desirable loads of small commercial and domestic services, with poor utilization of the apparatus on account of low average use of power each day during the year.

"Where waterpowers are used as auxiliaries to general power-distribution systems, the most economical conditions for both steam and hydro-electric generation can be fulfilled only where a relatively small proportion of the installed generating capacity is hydro-electric.

"8. These conclusions would not apply to the Mountain and Pacific States, where the potential waterpowers are enormous and of cheaper development and can be depended upon to furnish all local power requirements to a very distant future."

The present author would add that, in the summer of 1920, an acute power shortage was felt in California owing, principally, to the lack of rains in the previous winter and the hot summer which reduced the flow of the rivers in the central and northern parts of the State to the lowest stages known. This made it necessary to curtail the consumption of power in many industries by from 15 to 20 per cent. Such occurrences indicate the necessity for steam reserve stations in connection with most hydro-electric systems.

9. The author would add another point to the eight points taken from Torchio's paper.

While most of the States east of the Rocky Mountains either contain their own coal deposits, or are located next to States that have such resources, yet there are important regions that are dependent upon coal hauled from distant sources. Notable examples are the New England States, Minnesota and the Dakotas, as well as the central provinces of Canada. In these regions the coal supply has frequently been threatened by failures in transportation facilities, due to congestion, strikes or lack of cars or ships. For this reason, every effort should be made to develop the local power and fuel resources which consist largely of waterpowers and peat deposits. In Rhode Island there are deposits of low-grade semianthracite which is rather difficult to mine, while in the Dakotas there are large deposits of lignite with a high moisture content.

The waterpowers along the St. Lawrence and Niagara rivers are available to both countries. Canada's share is nominally greater as the lower St. Lawrence rapids are located in Canadian territory and these are not far from the city of Montreal. The waterpowers along the international boundary, however, are located within economic transmission distances of a larger number of American cities, and the United States should be entitled to a somewhat larger share of this power in exchange for the large quantities of coal which it exports to Canada.*

In New England many small waterpowers can be developed

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* Consult "The Coal Problem of Canada," by A. V. White, *Gen. Elec. Rev.*, June, **1919**, 465.

and the power fed into large fuel-power systems.* Tidal power may be developed in favorable localities along the coast from Cape Cod to the St. Lawrence River and, where local storage sites are not available, intermittent power may be fed into transmission networks fed by fuel and waterpowers. The facilities for daily storage on power streams might be used to supplement the tidal powers, and the river and tidal powers used in alternation.

In the New England states there is a stronger economic reason for the use of fuel oil from Mexico, for heating buildings and for industrial purposes, than in other parts of the states east of the Rockies. This gives New England an alternative source of fuel supply which is independent of the transportation facilities used for coal.

The use of peat and the availability of water power are so subject to seasonal variation that, at the best, they can only be depended upon to supplement New England's coal supply; and any network of electrical transmission lines must remain primarily dependent upon coal as a source of power. Peat and coal may be used, interchangeably, for making gas or in pulverized form.

Peat has been carbonized, in by-product coke ovens, to a product resembling wood charcoal. This might be used for smelting iron ores in the Mesaba region in northern Minnesota,† according to the methods used in Sweden, or in the electric furnace.

The Limitations of Our Fuel Resources.—An examination of Table XXV will show that the greater part of the coal resources of the United States and Canada are in the form of the lower-rank fuels of more recent origin, geologically, such as lignite and subbituminous coals. Moreover, these deposits are located in the western half of the continent and are not, therefore, available for use in the eastern half, where the greater part of the population and industries is located. The eastern deposits of bituminous coal are of sufficient extent for serving many generations, yet there is a distinct limit to their life and the present generation

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* Consult articles by C. P. Steinmetz in *Gen. Elec. Rev.*: "Electric Power Collection," August, **1919**, 565; "Hydro-electric Power Collection," December, **1919**, 960.

† Consult "Logical Methods of Utilization of Minnesota Peat," by H. H. Hindshaw, *J. Am. Peat Soc.*, January, **1920**, 37.

has no right to waste them just because there is plenty of coal in the ground to last for a few centuries to come.

Moreover, under present economic conditions, there are distinct limits to the rate at which coal can be mined and distributed; also, Table XXV shows that our resources of the higher rank coals, anthracite and semibituminous, compose only 1.3 per cent of the original deposits in the United States and Canada.

When the entry of the United States into the World War became imminent, early in 1917, those who were well informed predicted a fuel shortage, but it required the actual development of a shortage in the supply of coal to awaken the American people to the real limitations of the fuel supply. Even since the war we have had the seriousness of the situation kept constantly before us: (1) by the labor situation in the mines and on the railroads, (2) by the limitations of our transportation systems, and (3) by the consequent increase in the cost of fuel.

Nature, working through long ages, has prepared the various ranks of coal from the original peat deposits, lignite being the first stage, while our relatively limited deposits of semibituminous coal and anthracite represent the most refined solid natural fuels. Likewise, our extremely limited resources of petroleum and natural gas have been produced and concentrated in nature's laboratories from baser organic materials. These high-grade natural fuels can be utilized by man with such facility, and the subterranean reservoirs of natural gas and oil can be tapped so easily, that our limited supplies are being exhausted at a very rapid rate.

Petroleum is utilized on a multiple-product basis to a limited extent; nevertheless, fully one-half of our oil is burned for generating steam, which is a "low use" as compared with its latent possibilities in the way of further refinement. The development of cracking processes renders possible the extraction of a further yield of gasoline and other valuable products. It is considered probable that the production of petroleum in the United States has nearly reached its maximum and that it is likely to decline before very long. This fact, together with the rapid increase in the demand, has resulted in increases in price which may be expected to continue until fuel oil is reserved for "high uses" exclusively. This will throw us back upon coal for carrying the burden of the "low uses," such as generating steam in stationary boilers in large power and heating plants.

There are large reserves of petroleum in Mexico and in the northern part of South America, which may be drawn upon. These resources are well situated for supplying the needs of European countries, and of the American navy and merchant marine; but they are, probably, no greater in extent than the remaining reserves of petroleum in the United States. Owing to their own limited resources, some of the European countries are likely to become increasingly dependent upon America for their fuel supplies.

The most important oil fields in Europe are those in the regions of the Black Sea and the Caspian, in Rumania and Russia, respectively. Parts of these fields were damaged seriously during the war, when an effort was made to render them unavailable to the advancing Germans. Oil wells require constant care to keep them in working order and, when they are deliberately damaged, water is likely to find its way into the oil-bearing stratum and to cause a dispersal of the oil which nature has taken ages to concentrate. This unfortunate occurrence may further limit Europe's ability to be self-supporting as regards her oil requirements.

The facility with which oil may be shipped overseas in tank steamers will possibly render it uneconomical to ship Central American oil to the United States and then to export coal, from mines in the Appalachian field, to Europe. The more rational procedure will be to ship oil from the Central American fields to Europe and to use our coal at home. This may not always prove to be desirable, as Mexican oil can be shipped to the New England States, for instance, more readily than coal. This possibility, however, emphasizes the importance of developments which will facilitate the placing of the utilization of our resources of bituminous coal more nearly on a par with that of liquid fuel.

The greater part of the coal used today is burned in the raw state. Much of the coal is fired by hand and a large proportion of it is utilized in very inefficient ways so that the consumption is greater than should be necessary if advantage were taken of the more recent advances in the methods for preparing and burning fuels and for recovering and utilizing by-products. Considerable labor is required for mining, transporting, distributing, handling and burning coal, and this labor can only be employed to the best advantage when the coal is utilized on the most efficient basis.

It has been estimated that the mining and transportation of coal, in the United States, requires the labor of 1,500,000 men, and the use of over 1,000,000 cars and 40,000 locomotives. About one-half of these men are employed in the coal-mining industry. In 1917, the labor statistics were as follows:*

MINING INDUSTRY	ANTHRACITE	BITUMINOUS
Number of men employed	154,174	603,143
Average tonnage per man, per year	646	915

Coal, rather than petroleum, is our basic fuel. Liquid fuels made from petroleum have the great advantage of mobility. Mobile fuels can be made from coal by pulverization and by gasification, and certain kinds of liquid fuels may be recovered from the products of coal distillation. Electricity is the most mobile fuel product for the transmission of energy for power and heating purposes.

THE PRESENT STATUS OF THE COAL-PRODUCTS INDUSTRIES

Table XXVII indicates the total production of anthracite and bituminous coal during the years 1917, 1918 and 1919; also the proportion of the coal which is subjected to preparation by various methods before being burned.

Anthracite.—The anthracite industry is the most highly organized branch of the coal-mining industry. Anthracite is prepared and utilized largely on a multiple-product basis, the main product being the domestic sizes which, in 1917, constituted 69.7 per cent of the usable output. Table XXVIII gives the standard sizes specified by the U. S. Fuel Administration. The sizes smaller than "pea" and larger than "silt" are designated as steam sizes and are used principally for generating steam for power and heating.

The screens in actual use differ slightly from these sizes. A part of the final screenings is sold as "boiler fuel," this size also being designated as "birdseye," or No. 4 buckwheat. The larger part, however, goes to the stockpiles or culm banks and is known as "silt" or "slush."

The proportions of sizes in the output of the breakers remain fairly constant from year to year, the domestic sizes ranging between 73 and 75 per cent. of the total. The proportion of the

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* *Mineral Resources of U. S.*, **1917**, ii, 932.

steam sizes, however, is increased by the output of washed coal from the culm banks and river dredges, so that they represented 30.3 per cent of the total production in 1917. During 1917 and

TABLE XXVII.—COAL USED FOR MAKING PREPARED FUELS IN THE UNITED STATES IN NET TONS

	1917	1918	1919‖
Anthracite (Pennsylvania):			
Total marketable product.	99,611,811	98,826,084	86,200,000
Domestic sizes:			
Total shipments........	60,500,000†	56,205,000	
Washery product.......	1,220,000	1,270,000	
Producer gas and water-gas Briquets.........	137,660	209,690	
Steam sizes:			
Used at mines for steam and heat............	10,440,601	10,223,949	
Total shipments........	26,250,000	24,675,204	
Washery product.......	5,250,000	6,870,000	
Dredged from rivers....	171,100	382,500	2,000,000*
Pulverized coal.........	First commerc	ial boiler plant	started in 1919
Silt (waste)............	....	6,000,000‡	
Bituminous coal:			
Total production.........	551,790,563	579,385,820	458,063,000
Beehive coke.............	52,246,612	30,481,000	19,650,000
By-product coke..........	31,505,760	25,997,580	25,171,000
Coal gas and coke........	4,959,700		
Producer gas and water-gas..................			
Pulverized coal...........	10,000,000§	....	12,000,000§
Briquets.................	264,677	257,320	
Washed coal (mostly slack for making coke).......	25,483,000	22,017,293	
Used at mines for steam and heat.............	12,117,159	12;521,446	

* Estimated by Pennsylvania Geological Survey.

† Including local distribution in mining regoin.

‡ Estimated.

§ Estimated by Fuller Engineering Co.

‖ Estimated by U. S. Geological Survey.

The other figures are from statistics compiled by the U. S. Geological Survey.

TABLE XXVIII.—STANDARD SIZES FOR ANTHRACITE
Authorized by U. S. Fuel Administration, May 28, 1919

Kind	Size number	Through round, inches	Over round, inches
Broken	2	4¾	3¼
Egg	3	3¼	2¼
Stove	4	2⅜	1⅝
Nut	5	1⅝	¾
Pea	6	¾	½
No. 1 buck	7	½	¼
No. 2 buck (rice)	8	¼	⅛
No. 3 buck (barley)	9	⅛	1/16
No. 4 boiler fuel (birdseye)	10	1/16	

1918 the shipments of the various steam sizes from the Pennsylvanian anthracite districts were as follows:

TABLE XXIX

Buckwheat	Net tons	
	1917	1918
No. 1	13,070,000	11,062,021
No. 2	6,860,000	5,510,448
No. 3	3,330,000	5,174,403
No. 4	2,935,000	2,928,332

The greater part of the steam sizes are fired by hand. No. 1 buckwheat is used, to a limited extent, for domestic heating in specially designed furnaces of the magazine type, the Spencer furnace being a leading make. Where the smaller sizes are used as boiler fuel, the Coxe travelling grate stoker is frequently employed. This stoker gives excellent results with No. 3 buckwheat, which is the largest size available at a sufficiently low price for extensive use on mechanical stokers. Smaller sizes are sometimes burned on this type of stoker, but at somewhat lower efficiencies.

In former years, when the costs of labor and materials were less than today, the anthracite industry was in a more prosperous condition and little attention was paid to certain forms of waste incurred. The more cheaply mined seams are now becoming exhausted and, under present economic conditions it is necessary to go to further technical refinements for the prevention of waste. Two refinements are being introduced, in connection with the generation and distribution of the power for operating the mines and breakers, which will result in marked economies in fuel:

1. The substitution of electricity for steam as motive power in the mines.
2. The use of silt from the culm banks as boiler fuel in pulverized form, or in the form of producer gas.

In 1915, the proportion of the coal used for steam and heat at the mines and breakers was 11.25 per cent. of the total output. In 1917, this proportion had decreased slightly, owing to the electrification of some of the mines, so that 10.5 per cent. of the coal was required to mine the remainder.

Only a small proportion of the mines have been electrified, the remainder are still distributing steam through long lines of piping with considerable losses from condensation. The results which have been attained at electrified mines indicate that the consumption of fuel for generating power can be reduced tenfold.* A saving in labor is also effected; at one colliery 2.5 per cent of the men being released by electrification. This should tend to offset the increased labor required for mining the thinner or deeper seams in the future, while the fuel saving should more than offset the additional power required for deeper mining.

At the present time, steam sizes of anthracite are burned in mine power plants, the firing being done by hand. Recent developments have established the practicability of burning anthracite and other low-volatile fuels, under boilers in pulverized form. The present practice of hand firing in these plants is so inefficient that it is expected that a two-fold saving can be effected. Hence, it seems likely that by the adoption of both these improvements, the consumption of anthracite for mine power may be reduced to about one-twentieth of the former requirements, while the fuel required for steam heating may be reduced about one-half. In addition, the pulverized coal will be made from silt, which is now a waste product. All the steam sizes will, therefore, be released for sale, besides which the surplus silt will be rendered available

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* Consult: "The Use of Electric Power in the Mining of Anthracite," by J. B. Crane, *Gen. Elec. Rev.*, February, **1919**, 148.

for sale as a source of fuel for central stations located within an economical shipping distance.

Anthracite silt has also been gasified in a new type of horizontal rotary producer which is described in Chapter VI. The static type of producer is adapted only for gasifying domestic sizes and these are a refined type of fuel which is now more valuable for other purposes. Pulverizing and gasifying are simpler methods for utilizing anthracite silt than briquetting.

The calorific value of anthracite silt is usually about, 9,500 or 10,000 B.t.u. per pound, owing to its high-ash content, which often ranges from 25 to 40 per cent. When it is to be shipped any distance, it will be desirable to wash it before loading on cars, to remove bone, slate and dust. The fine dust tends to leak through the car bottoms in transit and is of slight fuel value owing to the fact that its ash content usually runs higher than that of the granular coal—often between 40 and 50 per cent. Heretofore there has been little effort made in the way of cleaning the small sizes of anthracite and there is a further opportunity for the development of effective cleaning methods (see page 608).

The proportion of fine coal may be expected to increase in the future with the opening of thin seams containing "seam dirt," which is of a size equivalent to "birdseye" (No. 4 buckwheat). In addition to the fine anthracite which is produced in the mining region as a by-product, screenings are produced at the coal yards of the local distributors. These result from the breakage incident to the transportation and handling of the domestic sizes of anthracite and are roughly proportional, in quantity, to the difference between the long ton and the short ton. Possibly the removal of these screenings originated the practice of selling anthracite at wholesale by the gross ton and retailing it by the net ton, since the yard screenings are retailed as steam fuel at much lower prices.

The burning of the smaller sizes of anthracite is discussed more fully in another Chapter, in connection with the burning of finely divided fuels (pages 515 to 608.

The mining of anthracite is much more expensive than the mining of bituminous coal. The steam sizes, however, being sold in competition with bituminous coal or burned at the mines.

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* The author is indebted to R. S. Walker, J. J. Wyllie, Jr., and C. W. Lotz, of M. A. Hanna & Company, Cleveland, O., for statistics and information concerning anthracite and its utilization.

do not bear a proportionate share of the cost of production. Consequently, the excess cost of mining must all be born by the domestic sizes.

Briquetting industries are now being established for making domestic fuel from silt and slush, and considerable advances are being made in the art. Briquets can be sold at prices which are comparable with those obtained for domestic sizes, and, if the industry is extensively developed, it may absorb much of the fine coal not required for the operation of the mine-power plants. The briquetting of a considerable proportion of the silt and smaller steam sizes should enable these sizes to bear their proportion of the cost of mining and, possibly, prevent further increases in the price due to deeper mining.

This possibility is, of course, dependent upon the cost of briquetting. Several processes are being used with various binders. The best briquets, possibly, are those made by two coking processes which have recently been developed. In one of these,* pulverized bituminous coal is used as a binder and fills the voids between coarser particles of anthracite of mixed sizes. The bituminous coal particles fuse and swell during coking and cement together the coarser particles of anthracite These briquets will stand rough handling and out-of-door storage.

The second process has been developed at Syracuse, N. Y., the product being known as "Anthracoal."† Coal tar pitch is used as a binder, in the proportion of 15 per cent of pitch to 85 per cent of anthracite culm. The coking is done, preferably, in ovens of the regenerative non-recovery type. The recovery of by-products will hardly pay for the following reasons:

1. The quantity recoverable is only one-third or one-half as much as from bituminous coal.

2. The hot gas may be burned for heating the retorts without the loss of sensible heat.

3. The output of "anthracoal" from ovens of a given size is 79 per cent greater than in the case of by-product ovens, for the reason that they may be operated at a higher temperature.

4. Non-recovery ovens are a more suitable commercial proposition in the anthracite mining districts. The cost of the

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* Information furnished by the inventor, H. M. Chance, 839 Drexel Building, Philadelphia, Pa.

† "Anthracite," by D. Markle, *Mining & Metallurgy*, Aug., **1921.**

by-product plant is eliminated, and this usually amounts to about 50 per cent of the cost of the ovens.

"Anthracoal" has a hard, dense, homologous mass with a silvery luster. The matrix, from the carbonization of the pitch, is practically pure carbon. When pushed from the oven, it develops only partly the fingerlike structure of coke. When struck with a hammer, or passed through crushing rolls, it breaks with an irregular fracture, similar to anthracite, but with very little fines.

Comparative eight-day tests were made in a kitchen range, burning chestnut, anthracite and "anthracoal" under exactly similar service conditions. The total fuel used was 288.5 lbs. of "anthracoal," as compared with 346.5 lbs. of anthracite, or 20.1 per cent more anthracite.

The cost of briquet manufacture, on the one hand, and of pulverizing anthracite slush, on the other, will determine the relative economics of the utilization of the available silt resources as domestic or steam fuels, respectively; and the distances to which anthracite may be shipped for use as steam fuel in competition with bituminous coal.

Bituminous Coal.—Table XXVII indicates that only a relatively small proportion of the bituminous coal produced is subjected to preliminary treatment, other than crushing, before being burned. Moreover, a considerable but decreasing proportion of the coal which is made into prepared fuel is carbonized in the primitive beehive coke ovens, with the loss of volatile matter from which valuable by-products may be recovered. The by-product coke ovens have been installed in increasing numbers, but they represent a much greater investment and must be kept in fairly continuous service in order to earn their fixed charges. The beehive ovens, therefore, carry the peaks of the demand for coke and may be left idle during the intervals of light demand.

By-product ovens have other limitations:

1. They are limited to the coking of certain types of raw fuels, and this is true also in the case of the beehive oven.
2. The yield of by-products is limited in quantity and character.
3. The fuel products, coke and rich gas, are applicable mainly to high uses and are too valuable for low uses.

Table XXX shows the annual production of coal in the United States during the 5 years from 1915 to 1919, and also the relatively small proportion of the bituminous production which is of a quality suitable for the manufacture of coke in by-product ovens. A matter of special significance is the fact that nearly all the coking coal is produced from the Appalachian field. Certain coals from Washington and Colorado are coked in by-product ovens,* and some recent experiments, which were carried out under the supervision of the Bureau of Standards, have shown that it is possible to make coke of good quality in by-product ovens from certain Illinois coals. The fact remains, however, that most of our coals are not available for refinement by the older methods.

TABLE XXX.†—PRODUCTION OF COAL IN THE UNITED STATES (IN MILLIONS OF TONS)[1]

	Year				
	1915	1916	1917	1918	1919
Bituminous	443	503	552	579	458
Anthracite (Pennsylvania)	89	87	100	99	86
Total coal	532	590	652	678	544

COAL SUITABLE FOR BY-PRODUCT COKE, 1917

	FIRST GRADE	SECOND GRADE	TOTAL
High volatile	99	23	122
Low volatile	43	12	55

As shown in Table XXV, the lower ranks of coal form by far the greater portion of the coal reserves. These coals are the most difficult ones to utilize efficiently in the raw state. Other forms of mineral fuels, of which we have an abundance, are peat and bituminous shale. These cannot be utilized in the raw state on any extensive scale.

POSSIBILITIES FOR THE MORE GENERAL UTILIZATION OF SOLID BITUMINOUS FUELS ON A MULTIPLE-PRODUCT BASIS

The present practice of burning raw coal under boilers sacrifices constituents of the coal which would be of greater value for

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* Ref. "Some Characteristics of American Coals in By-product Coking Practice," by F. W. SPERR, JR., *Jour. Franklin Inst.*, August, **1918**, pp. 162–163.

† From statistics compiled by U. S. Geological Survey. Consult *Mineral Resources of the U. S.*, **1917**.

other purposes if they could be extracted economically before burning the fuel. There are two general classes of valuable constituents in coal in addition to carbon:

(*a*) Hydrocarbons produced from the volatile matter during destructive distillation.

(*b*) Organic nitrogen compounds which yield ammonia during distillation or gasification.

(*A*) **Recovery of Hydrocarbon Products.**—There is a considerable field for processes which will treat bituminous coal and lignite at a lower temperature, and more rapidly and cheaply, without attempting to make hard coke. The residual carbonized fuel would be useful either for burning under boilers or as domestic fuel.

There are several processes being developed in the United States and in England for the distillation of coal at temperatures below a red heat. One feature of particular economic importance is that a greater portion of the hydrocarbons are recovered in the form of oils rather than as fixed gas. These oils are especially valuable, because of their high tar acid content, for use as disinfectants and insecticides, while the oxidizable constituents make them valuable for timber preservation. A large yield of creosote is obtained from the distillation of the tar and this is the best preservative known for timber. Creosote is also valuable as a flotation oil, for use in connection with the concentration of finely divided ores in the mining industry.

At the present rate of depletion of our forests, and with the coming exhaustion of the kinds of timber most suitable for railroad ties, there is a growing demand for creosote. A few kinds of timber do not require preservatives, but with most of the timber now available the life of railroad ties can be prolonged four or five times. Tar oils obtained from coal distillation are the only cheap source of creosote; and creosoting is superior to impregnation with soluble salts, like zinc chloride, because it is more permanent and will not wash out.

All the processes for the distillation of coal in closed retorts produce rich gas which is valuable for distribution to industrial and domestic consumers. Coal gas is a highly refined fuel and is too valuable for steam raising, except in cases where it is a by-product which is produced in excess of the requirements of the local markets for high uses. The hydrocarbons produced during the distillation of the volatile matter exist, in complex form, as constituents of the original coal. Their removal causes a shrinkage in the residual fuel values incident to their recovery in the form of refined products.

(*B*) **Recovery of Nitrogen Compounds.**—The nitrogenous compounds were originally formed by the activity of bacterial organisms on the roots of the ancient vegetation, or in the peat deposits. The nitrogen being an inert constituent, and forming only a small proportion of the coal substance, can be recovered during destructive distillation without a direct loss of fuel values, other than the thermal losses incident to the preparation of the combustible constituents in the form of more refined grades of fuel, such as coke, semi-coke, gas and motor fuel.

When coal is distilled, either at high or low temperatures, only a relatiyely small percentage of the nitrogen content is recovered by scrubbing the gas. The high-temperature processes recover from 15 to 20 per cent of the nitrogen in the raw fuel, while the low-temperature processes recover from 5 to 20 per cent, according to the method of treatment.

In order to recover a larger proportion of the nitrogen in useful form, it is necessary completely to gasify the fuel. This is done in by-product gas producers and the ammonia is absorbed from the gas in scrubbing towers of special construction. This process has been in use in England, Germany and a few other countries for a number of years, during which time it has been subject to constant improvement through the efforts of several engineering companies. Two by-product producer plants have recently been erected in the United States.

The most complete recovery of by-products from the various chemical constituents in raw fuels will be effected by a two-stage treatment. First, the material will be distilled at low temperature and the valuable hydrocarbons recovered. Secondly, the semi-coke residue will be gasified in by-product producers and the greater part of the nitrogen recovered.

The producer gas may be used as boiler fuel and the nitrogen will be recovered in the form of ammonium sulphate. This salt is one of the most valuable ingredients for fertilizers, the three most necessary elements for stimulating the growth of plants being nitrogen, phosphorus and potash.

The Substitution of Prepared Fuels for Raw Fuels.—The U. S. Geological Survey has compiled statistics on the amount of bituminous coal consumed by various industries in 1917, and these are summarized in Table XXXI. Torchio states (on page 271) that the total consumption of coal in 1915 was nearly equally divided between primary power and heating. This estimate was based on similar figures for 1915, which included both anthracite and bituminous coal, as well as upon estimates of the amount of power generated. These estimates make it appear probable that the largest item in Table XXXI, the consumption of coal for industrial purposes, is about equally divided between power and heating. Assuming this to have been true in 1917, the consumption of bituminous coal for all purposes was distributed between primary power and heating, in the ratio of about 60 and 40 per cent, respectively. Most of the

TABLE XXXI.*—BITUMINOUS COAL OF DOMESTIC ORIGIN CONSUMED IN THE UNITED STATES IN 1917[1]

	Use†	Millions of tons	Per cent of total
Used by industries:			
At mines for steam and heat	....	12.1	2.2
For beehive coke	....	52.2	9.5
For by-product coke	....	31.5	5.7
For coal gas	....	5.0	0.9
By electrical utilities‡	....	31.7	5.7
For domestic purposes	H	57.1	10.3
For industrial purposes	H and L	176.4	32.0
Used for transportation:			
By railroads	H	153.7	28.0
By steamships	H	10.9	2.0
Foreign trade:			
Exports:			
Bituminous	....	23.8	4.3
Anthracite	....	6.0	
Imports:			
Bituminous	....	1.5	

* From *Mineral Resources of the U. S.*, **1917**, ii, 1251–4.

† H = high use, for which the more highly refined fuels are desirable.
L = low use, for which cheap fuel is desirable.

‡ During the year 1920, the output of the public utility plants burning fuel represented about 62 per cent of the total output by electrical utilities, the remaining 38 per cent being generated from water-power (*Rept. Div. Powe· Res.*, U. S. Geol. Surv.).

anthracite produced was probably used for heating, and this will make the total use of coal, for these two purposes, approximately equal in 1917 also.

The use of fuel for power may be further divided into automotive and stationary power. Where coal is used for heavy automotive power units, such as steamships and locomotives, it has generally been burned as raw fuel, fired by hand and utilized in relatively primitive and wasteful ways. The advent of liquid fuels, derived from petroleum, has brought about marked advances in the utilization of fuel in heavy units and has revolutionized transportation in light units on the highways. The advantages of liquid fuels and electricity, for automotive transportation, may be said to have established the principle that this field constitutes a "high use" for fuel and to justify the conclusion that the use of raw fuels for automotive power should be superseded by prepared fuels and by electricity in their respective economic spheres.

The same reasoning applies in the case of the use of prepared fuels for direct industrial applications and for domestic heating, as will be brought out later. These three fields, therefore, constitute the "high uses" for fuel.

The remaining uses may be divided into the following general applications, which may be considered as "low uses:"

1. As raw material for the manufacture of prepared fuels for higher uses.
2. Generating steam in central stations for the distribution of electrical or mechanical power, or for pumping water.
3. Generating steam (or hot water) in central heating plants for warming buildings and for indirect industrial heating.

In these three cases raw fuel is being refined in bulk for higher uses: in case (1) as prepared fuels, and in cases (2) and (3) as energy for general distribution. In the last two cases raw fuels are generally used for generating steam, but cheap prepared fuels may be substituted, under favorable conditions, with an economic advantage:

First, when prepared in a form which can be utilized more efficiently than the raw fuel from which it is made, as in gasifying or pulverizing.

Second, when such preparation involves the utilization of the material on a multiple-product basis, valuable by-products being extracted and applied to high uses, while the greater bulk of the raw material is left as a residual product which may be applied to low uses in competition with raw fuels.

If 60 per cent of the bituminous coal be used for power generation, the proportion used for generating steam in central plants for power and heating should be at least 70 per cent. This will serve to emphasize the importance of the general problem of the efficient utilization of the fuel burned for steam purposes.

The oldest arts for making prepared fuels are those used in the gas and coke industries, where fuels are prepared for high uses. The second oldest art, probably, is the manufacture of producer gas. The pioneer in this field was Sir William Siemens, who was born in Hanover, Germany, in 1823, but spent most of the active years of his life in England. His most important invention was the Siemens type of open-hearth regenerative furnace, for melting and refining steel, which he introduced in 1856. Another invention was required before this could be entirely successful, and this was the use of gaseous fuel. The need for a cheap method for making gas resulted in the development of the gas producer on a commmercial scale, and one of the first installations was made at Chance's Glass Works in Birmingham in 1861.

Siemens' faith in gaseous fuel led him to anticipate that it would in time supersede solid coal for domestic and industrial purposes, cheap gas being supplied either from gas works or directly from the mines. In 1881, 2 years before his death, he made the following prediction:*

> "I am bold enough to go so far as to say that raw coal should not be used for any purpose whatsoever, and that the first step toward the judicious and economical production of heat is the gas retort or gas producer, in which the coal is converted into gas, or gas and coke, as is the case at our ordinary gas works."

Since this prediction was made there has been steady progress in this direction, as evidenced by the substitution of gaseous, liquid, pulverized or carbonized fuels for raw bituminous coal for many purposes. The rapidly increasing use of electricity has, however, opened the way for more progress in this direction than all other factors combined, since electricity is not only a fuel substitute, but is also the most efficient means for the transmission of energy, and renders possible the concentration of the generation of power in large central stations, where the most

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* Consult E. B. ELLIOTT, "By-product Coke Ovens," *Gen. Elec. Rev.*, July, **1918**, 480.

economical machinery can be used and where prepared fuels can ultimately be used on a large scale.

The development of next greatest importance in this direction has been the substitution of automotive power for animal traction on the highways. This is entirely dependent upon the use of highly prepared fuels, such as gasoline and electricity, and has released a great deal of cultivated land and farm labor, formerly required for raising food for draught animals, and made them available for raising food for our steadily increasing population. It has been estimated that, for each draught horse released, from 5 to 10 acres of farm land are rendered available for raising human food. The supply of gasoline is largely dependent upon the refining of petroleum, but motor fuels may also be obtained as by-products from the refining of solid fuels.

It is the purpose of the author to review the possibilities for the further substitution of prepared fuels and electricity for fuels now burned in the raw state, and to correlate the various methods which are now available, or are being developed, and which have not been generally used on a large scale. The field is such a large one that this review will be limited to processes which are adapted for refining bituminous coal for use in connection with the generation of primary power. In some cases the same processes are equally available for refining lignite, peat, bituminous shale or wood waste, and the application of the processes to the treatment of these raw materials is included. The products of all these processes are applicable to other industries than the generation of primary power, and a review of the economic field must necessarily include the utilization of all the products as well as the diversified uses for the main products.

The more important primary coal products are tabulated in the approximate order of their relative degree of refinement, in Table XXXII, commencing with "slack fuels" and run-of-mine fuels" in the lower left-corner. These represent crude material from the mines, while steam, mechanical energy and, finally, electricity, in the upper-right corner, represent the most refined products which are produced on a large scale. The degree of refinement increases from left to right as well as from the bottom of the table to the top. Thus the major portion of the primary non-fuel products, in the right-hand column, are of greater intrinsic value than the fuel products; otherwise it will not pay to extract them.

TABLE XXXII.—COAL PRODUCTS AND THEIR RELATIVE DEGREES OF REFINEMENT AND ECONOMIC VALUE

→ Increasing degrees of refinement →					
	→ Low uses →	← High uses →			
	A	B	C	D	E
	Steam fuels and products for further preparation for fuel purposes	Industrial fuels	Domestic fuels	Automotive power and special uses	Non-fuel products
Energy transmission:		← Electricity →			
		← Steam →			Mechanical energy
	← Hot flue gas (utilization of waste heat) →		Hot water Warm air		
Gases:		← Coal gas →		Acetylene	Ammonia
		← Blue gas →			
	← Producer gas →				
	← Blast-furnace gas →				
Liquids:				Motor fuel	Benzol
		← Fuel pastes →			
		← Tar oils →			
	← Crude tar →				Ammonia
	← Colloidal fuel →				Naphtha
Finely divided solids:					
	← Pulverized high-volatile fuels →				Ammonium salts
	Pulv. low-vol. fuels				
	← Granulated bituminous fuels →				Naphthalene
	← Anthracite, steam sizes →				Retort carbon
	← Coke breeze →				
	← Culm →				
Lump solids:					
	← Pitch →	← Carbonized briquets →			Pitch
	← Dense semi-coke →				
	← Soft semi-coke →	← Metallurgical coke →			
	Washed raw fuels	← Gas coke →			
	Crushed raw fuels	← Anthracite →			
	Run-of-mine fuels	← Raw fuel briquets →			
	← Slack fuels →	Sized bit. fuels			

Some of these products are used as raw materials for the manufacture of a very great number of secondary or tertiary products. The tar oils include the heavier distillates from coal-tar, ranging between the light oils, on the one hand, and pitch, which is the residual product. Benzol and solvent naphtha are the primary non-fuel products from the light oils. Benzol and the tar oils are among the most important raw materials used in the chemical industries for the manufacture of secondary and tertiary organic products. The quantity required for making high-grade chemicals, such as dyestuffs, however, is not great enough to support large new coal product industries. Therefore, markets must be developed for the cruder products which can be used on a large scale, such as creosote oil, lubricating oil and motor fuel.

THE USE OF FUEL IN VARIOUS INDUSTRIES

Returning to Table XXXI, and considering the use of coal in the various industries, we can begin at the foot of the list with transportation.

Steamship Fuel.—Petroleum is especially adapted for carrying on board ship, both for exportation in bulk and for steamship bunker fuel. Liquid fuels can be pumped aboard ships through pipes and can be burned under the boilers with simple automatic equipment. Also, it is a more concentrated fuel for carrying on ships. These facts are of sufficient weight to classify marine uses and overseas shipment as relatively "high uses" for liquid fuels.

It has been pointed out, however, that the world's petroleum resources are much more limited in extent than the coal resources. While the use of oil for steamship bunker fuel is a higher use than the generation of power in central stations, where it competes with coal burned on automatic stokers, yet the refining of petroleum is a still higher use. The continued increase in the demand for gasoline will raise the price of this highly refined fuel to a point where the refiners can afford to pay more for crude oil than the ship owners can.

Having had a period of emancipation from the firing of coal on shipboard by hand, no one will care to return to it and mechanical firing will become imperative.

The United States Shipping Board, in anticipation of this eventuality, has obtained the cooperation of the manufacturers of mechanical stokers in the adaptation of their equipment to marine boilers. The problem of the mechanical firing of lump coal on shipboard has been successfully solved, but the coaling of the ship, the trimming of the bunkers and the handling of coal on board, still leave much to be desired as compared with the simplicity of the handling of oil by pumping it through pipes.

Before solid fuels can be utilized on shipboard with anywhere near the same facility as liquid fuels, they must receive preparatory treatment in central preparation plants on shore. Some experimental work has been done looking toward the utilization of finely divided solid fuels on board ship, both in granular and in pulverized form.

Such fuels may be handled by pneumatic conveying methods and they can be fired pneumatically in the furnaces. The handling and storage, however, involve considerable innovations, especially in the case of pulverized coal which must be burned in specially proportioned furnaces. Granular, or finely crushed coal, can be burned on grates in existing furnaces and it, therefore, involves fewer departures from existing practice.

It is likely that prepared fuels whose use involves the fewest departures from existing practice will be adopted first as a matter of natural evolution, provided there is a sufficient economic incentive for making a change. The most promising developments in this direction involve the use of composite fuels containing both coal and oil.

The initial development in this line was "colloidal fuel," which is described in another chapter. This is a mixture of about 30 per cent. of pulverized coal with fuel oil. Since the coal is held in suspension, the mixture remains liquid and may be handed and burned with the same equipment as fuel oil, the function of the coal being that of a diluent which displaces a part of the oil.

A more recent development is the "Trent amalgam," in which the proportions of coal and oil are reversed (see page 628). As this contains approximately 70 per cent of pulverized coal, it may be attractive as a substitute for oil where coal is a cheaper fuel than oil. Moreover, low-grade coals of all ranks may be utilized, the greater part of the inert mineral matter being removed during the preparation of the amalgam. Many coal deposits which are conveniently located with reference to seaports in all parts of the world, should be available for the preparation of high-grade fuel for bunkering ships.

This amalgam is in the form of a paste which is sufficiently fluid for pumping through pipes and for spraying into a furnace. It can be burned on grates like solid fuel, all of the ash being carried up to the stack as a fine dust. The amalgam is a dustless material, and, when compacted under its own weight, it should exclude air and moisture and therefore have no tendency to ignite spontaneously in storage.

These lines of attack on the problem of utilizing coal, with the same facility petroleum should be continued, as there is not enough oil available to run the world's shipping, to furnish the gasoline required for automotive vehicles, and for lubricating oils and other petroleum products. Moreover, it will not be very many years before oil will be in such demand for high uses that even the merchant marine will have to fall back upon coal, or fuels prepared artificially from low-rank coals.

Where coal is now used on ships, the high-rank coals are preferred, usually semibituminous coals which are classed as semismokeless when used for hand-firing. These are of relatively limited distribution throughout the world. Our own deposits are fortunately located nearest to the seaboard of any part of the Appalachian coal fields. Their limited extent, as compared with the lower-rank fuels, is clearly shown in Table XXV. These two facts are responsible for the rapid rate at which these coals are being used up.

The two most important improvements in marine motive power, which have been introduced in recent years for saving fuel and labor, are as follows:

(*a*) The use of liquid fuel for firing boilers, or for internal combustion engines; and

(*b*) The use of high-speed prime movers with mechanical gearing, or electrical transmission, for driving low-speed propellors.

High-speed turbines are used in large vessels with mechanical or electric drive. In small vessels, such as fishing trawlers,* tugs and lighters, high-speed oil engines with electric drive may be used to good advantage.

The slow-speed marine Diesel engine has been developed in Europe, in units ranging up to a capacity of between 2,500 and 3,000 shaft hp., for direct drive to a single propellor. A few large engines have been built in the United States, generally from European designs. These engines give excellent fuel economy, the oil consumption under operating conditions, on some vessels, averaging about 0.4 lb. per shaft hp. per hour. The corresponding figure on the best steam vessels is about 1.0 lb.; and on a small vessel with high-speed Diesel engines and electric drive the fuel consumption will average a little better than 0.5 lb. of oil.

In large steam vessels the oil generally used ranges in gravity from 16 to 21°Bé. The builders of Diesel engines claim that they can burn equally heavy oil. In practice, however, the operators of marine oil engines prefer lighter and more refined grades of oil, ranging from 24 to 33°Bé., which are considerably more expensive. The heavy oils produce carbon deposits which cause continual trouble with the valves and oil injectors

The steam vessel can burn low-grade oils from Mexico or

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* See "The Mariner: The First Electrically Operated Trawler," by J. Liston, *Gen. Elec. Rev.*, May, **1920.**

California, or colloidal fuel made from these oils, while the motor ship can use the heavy oils only under a disadvantage and with a considerable sacrifice in efficiency during the period of a long run. With the growing demands for the lighter oils for higher uses, and for refining, large motor ships may soon be thrown back upon heavy oil as fuel. The large Diesel engine is also a more complicated machine to operate and maintain than a turbine with electric drive, and the fixed charges and operating expenses, other than fuel, are greater.

The burning of oil in small motor ships is a higher use than in large ships, for the reason that the advantages, as compared with steam motive power, are greater. The small motor ship can, therefore, afford to use a more expensive grade of oil. Small vessels are used on short runs, or for intermittent service, and have, therefore, the possible alternative of using heavy oil and removing the carbon deposits during their more frequent stops in port.

The relative advantages of (1) heavy oil or colloidal fuel for large steam vessels, (2) light fuel oil for smaller motor ships, and (3) gasoline for still smaller motor boats, form a very interesting example of the relative economic fields for prepared fuels of increasing degrees of refinement. The more highly refined fuels are needed for use in small units; while, with large units, the lower the grade of the fuel which can be utilized, the greater is the economic advantage.

The use of liquid fuel in large vessels is advantageous at the present time, but it must soon be supplemented with prepared fuels made from coal and supplied on a large scale from properly located distributing points. Small vessels, however, can better afford to continue using oil. Coal gas, compressed in cylinders, has been suggested as a substitute for gasoline on motor boats used for local service.

Fuel economy is even more important on shipboard than in power stations because the bunker coal occupies valuable space which can often be utilized for carrying revenue cargo. It has been estimated that a saving of one-half of 1 per cent in fuel consumption, when capitalized, will pay for all the machinery in the ship. This emphasizes the advantage of the more economical electric drive, as compared with reciprocating engines, or with low speed turbines with direct drive. It also emphasizes the importance of compact fuels like oil. If coal is to be substituted for oil, it will probably be more practical to make a partial substitution in the form of Trent amalgam or colloidal fuel, rather than as a more bulky solid fuel.

Railway Fuel.—The railways use more coal than any other industry and they use it very wastefully. They also burn considerable oil for which there has been an economic reason in regions where oil has been cheap. The price of oil, however, is rapidly increasing, even in the southwestern States, where the supply is becoming inadequate.

Briquetted fuels, made from low-grade coals, have been used on European railways for many years. The briquets are molded in the form of large rectangular blocks and are stacked and handled by manual labor.

Pulverized coal has been used experimentally on locomotives in the United States, and a Brazilian railway is using pulverized coal equipment* on a number of locomotives. In Sweden some locomotives are burning powdered peat. Mechanical stokers are used for firing coal on locomotives to a limited extent in America, but they have not proved to be very economical. In all these cases hand labor is avoided.

While high-grade coals are utilized inefficiently on steam locomotives, low-grade coals are burned still more wastefully. One of the very greatest opportunities for saving fuel is offered by the electrification of the steam railways. On lines now using electricity as motive power the available statistics indicate that, on the average, fully two-thirds of the coal now used by steam locomotives can be saved by further electrification.

This figure is based on the assumption that the requirement for coal at the power station will average 2.5 lb. per kilowatt-hour generated.† With good coal some modern central stations are doing better than 1.5 lb. per kilowatt-hour. Thus, a railway operated with steam locomotives consumes at least three times as much coal as when operated electrically and the same grade of coal is burned in the power station. In localities where water-

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* This was supplied by the International Pulverized Fuel Equipment Corp. of New York, N. Y.

† Consult: A. H. Armstrong, "The Last Stand of the Reciprocating Steam Engine," *J. Am. Inst. Elec. Eng.*, March, **1920**, 209. Also W. J. Davis, Jr., "Railroad Electrification as a Fuel Conservation Measure," *Gen. Elec. Rev.*, March, **1919**, 196; and W. D. Bearce, "Possibilities of conservation of Fuel by Railway Electrification," *ibid.*, November, **1917**, 859.

power is available, there is the further opportunity of eliminating the use of fuel for operating the railways.

Many of the railways now burning oil are located in the western States, where large undeveloped waterpowers are available. The use of oil should be superceded by hydro-electric power as soon as the necessary capital can be provided for carrying out the change.

Nor is fuel conservation the only reason for electrification. The movement of railway coal, the hauling of locomotive tenders and their contents, together with the non-driving part of the weight of steam locomotives, represents about 14.5 per cent of the total ton-mile movement. At least 12 per cent of the total movement could be eliminated by electrification and the economic capacity of the railways increased approximately one-fifth without increasing the track milage. Moreover, this increased capacity can be maintained through the winter months, when the steam locomotives are least efficient. The smoke nuisance is eliminated, and the saving in the cost of fuel, repairs and other operating items, has more than paid the fixed charges incurred by the electrification of railways in the past.

Industrial Fuels.—In Table XXXI the percentage of the bituminous coal used "for industrial purposes" is greater than for the railroads. This figure, however, is made up of two distinct items:

1. Fuel used for direct industrial heating.
2. Fuel used for generating steam in factory power plants, both for power and for indirect heating.

The first is a high use for fuel, since many special requirements must be met, and the use of highly refined fuels is economically sound. Such fuels are gas, oil, colloidal fuel, pulverized bituminous coal and electricity. The second is a low use because cheap fuels can be used for generating steam.

Industrial Steam.—In the case of pulverized coal, the preparation plant is located at the plant where the fuel is used and it may often be advantageous to use this fuel for firing boilers as well as for industrial furnaces. Pulverized fuel can be more economically prepared on a large scale, so that there is a distinct advantage in concentrating the preparation of a large part of the fuel used in the plant. Factory boiler plants are not always operated on as efficient a basis as is the case with central stations whose primary business is the generation of steam and power. The regulation and control of pulverized coal fires in boiler furnaces is simpler than when coal is burned on grates or stokers, and better efficiencies may be maintained with the class of operators available, and with a limited amount of oversight.

The steam generated in factory power plants is often used on a multiple-product basis, the high-temperature heat being utilized for generating power and the exhaust steam for heating. This is a very economical method, the only limitation being that the proportion of the heat which is available for generating power is relatively small and the power becomes a by-product which it does not always pay to recover. The steam must usually be exhausted at a pressure of a few pounds above the atmosphere, and this reduces the available energy by about one-half, as compared with the energy recoverable when operating turbines on a condensing cycle. Where steam is used for manufacturing purposes throughout the year, exhaust steam should be used if it is available. If additional exhaust steam is available in winter, it should be utilized for heating buildings.

With present efficiencies, especially where old types of engines or turbines are used, the amount of exhaust steam may be in excess of the winter requirements. In old plants it may be inconvenient or expensive to make provision for operating on a condensing basis in summer and on a non-condensing basis in winter. There are two factors which may circumvent these limitations in the future:

(*a*) The development of more efficient prime movers, and

(*b*) The location of manufacturing plants in a zone about a central station in which the functions of supplying heat and power may be concentrated.

In some industries considerable amounts of steam are required for process-heating at temperatures above 212°F. A prominent instance is to be found in the rubber industry, where steam is used for vulcanizing operations at pressures from 50 to about 80 lbs. per sq. in., which can often be most economically obtained from turbines exhausting at these pressures. In such cases it would be most advantageous to obtain power as a by-product from boilers and turbines operating under high initial steam pressures, thereby making possible the recovery of a larger amount of power than is practicable at ordinary steam pressures. This subject is discussed further in the latter part of this Chapter.

Fuels for Industrial Furnaces.—Fuel oil and natural gas are used in industrial furnaces to a large extent, and, while industrial heating processes represent a high use for fuels made from coal, they represent a lower use for these scarcer natural fuels than some other applications. Thus, oil should be released for refining and natural gas for domestic uses. Pulverized coal is being rapidly substituted in large industrial furnaces and for the rough work in small furnaces, where the ash formed in the flame is not objectionable.

In some furnace operations, where the presence of dust and ash within the furnace is not seriously objectionable, pulverized coal and hot, raw producer gas are competitive fuels, as in the open-hearth steel furnaces and in smelting ores, pulverized coal having the advantage as regards economy and flame temperature.

Where cleanliness is essential in the furnace, cold clean gas is the best form of refined fuel. Producer gas (generated, preferably, in by-product producers) is applicable to furnaces requiring gas in large quantities, and which operate on a fairly continuous basis. Owing to its leanness, it is necessary to use regeneration in order to obtain high temperatures. It is especially applicable to glass-melting furnaces and to kilns for vitrifying ceramic ware.

Where gas is used in small furnaces, regeneration is often inconvenient or expensive and it is necessary to use a richer gas which contains few diluents. These furnaces are usually operated intermittently (*i.e.*, during daylight working hours only) and require higher temperatures than can be obtained with cold producer gas. The latter also cannot be used in blowpipes. The various kinds of gas commercially available for small furnaces and blowpipes are:

1. Coal gas (500 to 600 B.t.u. per cubic foot).
2. Carburetted water-gas, of similar calorific value.
3. Blue gas (about 300 B.t.u.).
4. Dayton oil gas (400 to 500 B.t.u.).

The first two are the common forms of city gas and have similar characteristics, while the third and fourth are primarily industrial gases. Blue gas, while having the lowest heat value of the four, burns with the highest flame temperature of any form of cheap industrial gas. Consequently, cold blue gas may be used much more efficiently than cold producer gas. All four of these gases may be used in small furnaces with from two to four times the thermal efficiency of fuel oil.

Dayton oil gas* (see page 1036) is made by gasifying fuel oil by a new process which, considered chemically, resembles the making of producer gas from coal. Since it is made by gasifying oil while mixed with air, it contains considerable nitrogen and other diluents which being down the thermal value of the oil gas, making it more nearly comparable with coal gas. This process is being used in a few industrial plants in preference to purchasing city gas. Since its thermal value is only slighly lower than the usual municipal standards, it may be used interchangeably with city gas. As the fixed charges on an oil gas plant are relatively low, by comparison with coal gas plants, an oil gas plant may be installed in an industrial establishment for carrying the intermittent and peak loads, while city gas may be purchased for carrying the steadier parts of the load.

This type of gas is, primarily, a substitute for the direct burning of fuel oil in small heating furnaces, since the gas may be burned much more efficiently than the oil. Moreover, cheaper grades of oil may be gasified than may be burned direct in small heating furnaces.

The possibilities for making gas from coal by new methods, and from new types of coal products, such as semi-coke, are discussed in Chapters VI and VII.

Some of the furnace operations where a clean fuel, such as gas, is necessary, or is sometimes preferable to pulverized coal, are the following:

1. Glass melting and ceramic kilns, where ash or dust can stick to the product. The latter, however, is often protected by saggers or muffles.
2. Chemical and metallurgical processes, where ash can contaminate the product.
3. Small forging furnaces, where the fuel must be burned in contact with finished work, when accurate dimensions are necessary, as in small drop forgings. Ash or slag may stick to such work, or to high-speed tool steel, and cause pitting. Ash troubles, however, may often be mitigated by suitable furnace design.
4. Gas is the only practicable fuel for use in open flames, being far preferable to gasoline wherever a gas supply is available.

* General Oil Gas Corp., 511 Fifth Ave., New York City.

Open-flame uses include torches, blowpipes and various small heating applications.

5. City gas may be purchased in small quantities from a public utility company, while a special gas, or pulverized coal, must usually be prepared on a fairly large scale before it can be done economically.

6. Gas may be economically distributed to scattered furnaces.

Electric Industrial Heating.*—Electricity is being applied to a constantly increasing number of industrial heating processes. Among heating agents it represents the most highly refined example and has certain economic fields in which it can compete to advantage with the direct combustion of fuel. Owing to the low thermal efficiency attained in generating electricity from coal, it is obvious that the cost of electricity, on the basis of available heat units, is almost always greater than that of fuel. Nevertheless, electric heat offers so many opportunities for improving the quality of the product, for increasing production, for additional safety and comfort of employees, and for more efficient utilization, that it already has a wide and important economic field. The possibilities for increasing the efficiency with which fuel may be utilized for generating power should increase the relative economic advantage of electricity as a heating agent as compared with the direct use of fuel.

The temperature of the electric furnace can be readily controlled by varying the rate of the power input, and by standard and well-tried devices this control can be accomplished automatically; in heat-treating and similar furnaces the temperatures can be automatically maintained with only a fraction of a per cent variation from the desired value.

Theoretically, any desired temperature can be generated by simply forcing the requisite amount of power into the furnace. Practically, the maximum temperature is limited, in the case of furnaces employing a solid metallic resistor heating unit, by the melting or softening point of the resistor; and in other furnaces by the melting or softening point of the refractory materials of which the furnace is constructed. However, the use of the arc, or of carbon resistors, and high-grade refractories, enables the production of a temperature which cannot be obtained in any other way.

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* Prepared with the assistance of H. A. WINNE, Power and Mining Dept., General Electric Co.

Therefore, the electric furnace is particularly suitable for very high-temperature work. Obviously the losses of a fuel-fired furnace increase more for a given increase in operating temperature than those of the electric, as the fuel-fired furnace has a loss in the heat carried away by the flue gases which are not present in the electric. Consequently, the electric furnace has found application in high-temperature processes, such as the making of carborundum, graphite, silicon and calcium carbide, and the manufacture of ferro-alloys of high melting-points, as ferro-tungsten, ferro-vanadium, ferro-molybdenum, and others.

The fact that a high temperature can be obtained and readily controlled, that the furnace can be made neutral or reducing as required, and that the atmosphere is free from products of combustion, has led to the rapid introduction of the electric-arc furnace for producing especially high-grade steels which formerly could be obtained only by the expensive and laborious crucible process. The growth in number of electric steel furnace installations is shown by the fact that, while in 1913 there were only about 20 such furnaces in operation in the United States, in January, 1921, there were 356 furnaces installed or contracted for.

The electric furnace is also being rapidly adopted for melting and making brass. While the actual cost of the electricity used may be greater than that of other fuels, the saving in metal losses due to the better control of temperature, the easier maintenance of a tight furnace, the higher quality of the metal produced, the improvement of labor conditions, and other factors, in a great many cases make the total cost of electric melting less than for other methods.

Even in lower temperature operations, where a high-quality product is desired and where temperature control and clean atmosphere will better the quality, electric heating is being used to a large extent. For example, large numbers of japan baking ovens are now electrically heated. The increase in production, the smaller number of rejected pieces, and the higher quality of the finish obtained, make the electric more economical than the gas oven, even though the actual electricity used costs more than gas would.

Electric heating is also used in furnaces for heat-treating iron and steel, where a high-quality product is necessary. A number of vertical cylindrical electric furnaces, from 20 to 90 ft. high, and 5 to 10 ft. in diameter, were installed during the war period for heat-treating large guns. The temperature and the rate of heating are automatically and accurately controlled, and are maintained absolutely uniform throughout the length of the furnace, and oxidation of the surface of the metal is prevented. Electric furnaces are in use or being installed for heat-treating gears, crankshafts, anchor chains, needles, wire, brass and copper tubing, and other articles. In all cases the electric furnace has proved very satisfactory.

Electricity is also used to advantage in connection with minor heating applications, such as muffle furnaces, tool-tempering baths, rivet heaters, solder pots, soldering irons and glue pots. In these cases the heat can be applied just where it is needed, with a maximum of safety and convenience and the required temperature maintained with a small consumption of current.

Electric-welding processes represent a special application where intense local heating is required. The fuel process which competes with electricity for welding is the oxy-acetylene method, and the manufacture of oxygen and acetylene gases is necessarily expensive. Acetylene is a highly refined fuel made from calcium carbide; this, in turn, being made from coke in the electric furnace.

The use of electricity as a heating agent has also rendered possible the development of electrochemical industries based on thermal processes which are dependent upon the production of high temperatures in a neutral atmosphere. These processes are beyond the field where fuels can be directly applied and can be carried on only in the electric furnace. Some of the leading examples are the manufacture of carborundum, alundum, graphite, calcium carbide and siloxicon.

A particularly interesting process of this general type, which has been under development for some time, is the manufacture of phosphoric acid from phosphate rock. The charge, consisting of rock and fluxing materials, is preheated (and sometimes melted) by the combustion of fuel. The materials are then subjected to a much higher temperature in an electric-arc furnace, where the necessary chemical reactions are effected and the phosphorus is driven off in the form of vapor. Hence, electrical energy is utilized only for the generation of high-temperature heat.

Thus, in addition to being the sole heating agent possible of application to some industrial processes, electricity is superior to direct fuel heating in many other processes; for, although the actual cost of electricity for heating a given weight of product is usually greater than that of other fuels, the overall cost per unit of finished product is lower for the electrical method, due to improved quality, fewer rejects, increased production, and decreased labor cost.

The Heat Pump.—While the low efficiency with which power may be generated from fuel imposes limitations upon the direct application of electricity as a heating agent, yet the thermodynamic cycle is reversible. The reversed thermal cycle is employed in refrigerating machines for extracting heat from a low temperature level and discharging it at the temperature of the cooling water. As long ago as 1856, Lord Kelvin suggested the use of a similar cycle at temperatures above that of the air or water. This would constitute a warming cycle for heating buildings, etc.; low temperature heat being extracted from a relatively large volume of air or water and discharged at a higher-temperature level by means of a heat pump. The air or water forming the source of the heat would be cooled only a few degrees, while the heat would be discharged into a relatively small mass of material which would be maintained at a higher temperature.

As in the case of refrigeration, the less the difference between the upper and lower temperatures, the greater is the theoretical ratio of the heat obtained locally, from the low temperature source, to the heat equivalent of the power required for elevating it to a higher temperature level. The heat delivered at this level is the sum of the heat equivalent of the power required and the heat obtained locally, neglecting minor losses due to radiation from the machine. Internal power losses in the compressor are converted directly into heat which is utilized in the heating process, while the power which is effectively utilized in the compression of the air or vapor medium has its thermal effectiveness multiplied to several times its original equivalent.

This general method has only recently been applied to commercial uses in Germany and Switzerland* in connection with industrial processes involving the evaporation of liquids. This

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* "The Heat Pump in Theory and Practice," by FRITZ KRAUSS, *Power*, Feb. 22, **1921**, 298.

application has been made possible by the development of the high-speed centrifugal compressor.

The vapor generated in evaporating tanks contains a large quantity of latent heat which is often rejected for the lack of a practical method of regeneration. In processes where the temperature at which the process is carried on is of no consequence, as in the distillation of water for purification, multiple effect evaporation is frequently employed. A series of evaporators is used, the vapor from each being condensed in the heating coil of another operating at a little lower temperature.

The use of the heat pump makes it practicable to regenerate the latent heat from a single evaporator. The vapor evolved is passed through a centrifugal compressor, in which it is raised to a sufficient pressure and temperature to establish a temperature gradient in the metal of the heating coils for effecting the necessary heat transfer and the condensation of the steam. When evaporating water it is necessary to effect the initial heating by direct means. After the water has been raised to its boiling point, however, the evaporation may be maintained by the heat pump with the exclusive use of electrical or mechanical energy.

In evaporating water at atmospheric pressure, and using an electrically driven compressor with an efficiency of about 50 per cent., it is theoretically possible to evaporate from 8 to 10 times as much water as can be evaporated by the direct application of the same amount of electric power in a resistance. Up to the present time, it has not been practicable to utilize electricity in this way for the lack of suitable compressors. Some form of rotary pump might, however, be adapted to this work.

Certain types of steam-turbine driven centrifugal compressors may be used, although the moderate pressures required (from 6 to 15 lb. per square inch) are beyond the range of any but the largest sizes of these machines when run at the usual speeds. Recently, some smaller machines have been developed which operate at very high speeds, and this is probably the type being used in Europe for this purpose.

Domestic Fuels.—The figures in Table XXXI include only bituminous coal and this also should be subdivided into two items:

1. Fuel used for heating houses; in furnaces, stoves and open fires.

2. Fuel used in steam or hot-water heating plants in larger buildings, where a fireman is usually on duty.

In the first case refined fuels are desirable because raw bituminous coal is burned very inefficiently in domestic use. When burned in furnaces, much of the volatile matter is driven off in the form of smoke.

Anthracite, being a naturally refined fuel, is used wherever it can be obtained at a reasonable price. Its production, however, is limited to a few districts in eastern Pennsylvania. There are some very local deposits in the West and in Alaska. The Pennsylvanian deposits, if the present rate of production is maintained, will be exhausted in a century. It is probable, however, that the production has already passed its maximum point, both as to quantity and quality, and that these factors will continue to decline. During the last few years there has been a noticeable increase in the quantity of bony coal shipped with the anthracite. The ash content is often so great as to present a considerable disadvantage in the use of this otherwise excellent fuel, although this may be mitigated by more careful preparation.

Carbonized Fuels.—Coke is coming into more common use as a domestic fuel and gives excellent results. It can be made from bituminous coals of low-ash content, and the amount of ash to be removed from the furnace is very noticeably less than with anthracite. Gas coke is a by-product of the gas industry, and much of it is used for making water-gas at the same plant and for making producer gas for firing the retorts. According to Table XXXI, the gas industry uses less than 1 per cent of the bituminous coal produced, so that the surplus coke is only a small factor in the fuel supply.

Metallurgical coke, made in the old beehive ovens, or in the modern by-product ovens, is a much larger factor than gas coke. When made for domestic use, the raw mixture and time of carbonizing are varied to give a softer product than is used for foundry or blast-furnace work. Coke has some minor disadvantages which have made it difficult to educate the public to appreciate its true value as a substitute for natural fuels. These are its bulkiness and the fact that it is dusty and more awkward to handle. Also, it burns more rapidly than anthracite. This, however, is an advantage in some ways, although it requires a little more frequent attention. These factors make it necessary to allow a differential, in price, of about a dollar a ton when selling coke in competition with anthracite. It should, logically, compete with anthracite on an even basis, but the cost of the advertising which would be necessary would, possibly, offset the gain.

A number of new methods are being developed in the United States and in England for making carbonized fuels from bituminous coals and lignites. These processes are based on the distillation of coal at low temperature and are described in Chap. VII. These fuels are quite different in character from coke and obviate some of the limitations of the latter when used as domestic fuel.

Gas for Domestic Heating.—The facility with which gas can be distributed and utilized makes it the most highly refined fuel available for domestic heating. Natural gas has been used very extensively for domestic furnaces, but the supply is being exhausted so rapidly that it is already being supplemented or superceded by artificial gas in some localities. Owing to its relatively high price as compared with solid fuels, artificial gas has only been used in domestic furnaces in occasional installations. Future possibilities in the use of artificial gas for heating houses are dependent primarily upon the development of cheaper methods of manufacturing gas and will be considered in the following chapters.

The use of gas as an auxiliary fuel is a simpler problem than that of the complete substitution of gas for solid fuel in domestic heating. In either case an appreciable reduction in the traffic on city streets may be rendered possible by the elimination of a part of the coal and ash handling and by the more continuous and intensive use of the gas-distributing mains.

The simplification of the control of house temperature and the reduction in the labor of tending fires, are very important considerations in household economics.

Electric Heating.—Electricity is used for heating houses in places where surplus hydro-electric power has been developed primarily for pumping water for irrigation during the summer months and is available for heating purposes during the winter.

Ordinarily, however, electricity is applicable mainly for local heating on a small scale, as in bathrooms and for cooking and ironing. The small incandescent radiators fitted with reflectors, however, are useful for keeping one or two people comfortable in a cool room.

While the electricity used in this way is generated from coal with low thermal efficiency, the loss is counterbalanced by the fact that the energy delivered to the radiant heater is efficiently converted into high temperature heat which is radiated only in the desired direction. With the development of prime movers which can utilize a larger proportion of the thermal energy released when burning coal and convert it into electrical energy (see page 325), the radiant electric heater may be more frequently used as a convenient and economical source of radiant heat.

Electricity is also put to some indirect uses in connection with domestic heating, as where electric fans are utilized for supplying draught for furnaces or for circulating air. Fans may be used for circulating warm air through ducts or locally in the rooms. In connection with warm-air heating systems, the ordinary portable type of electric fan may be used to good advantage for maintaining an even distribution of the temperature in a room by preventing the stratification of the air, with highly heated air at the ceiling and cold air below. Where steam or hot water radiators are used, this can be accomplished by setting the fan on the floor in front of a radiator and directing upon it an upwardly inclined blast of air. This augments the heat transfer, thereby increasing the output from the radiator, as well as maintaining a circulation of the warm air in the room.

Building Heating Plants.—High-pressure, hand-fired, steam boilers are generally used in large buildings and a fireman is kept on duty. Where the plant is too large to be tended by one fireman, automatic stokers are sometimes used. Hand stokers are also used to reduce the labor of firing.

When fuel oil can be obtained at a price which is competitive with coal, it has been given the preference. Mexican oil, at the present time, is coming into use in the cities on the Atlantic seaboard. The use of oil in firing boilers for heating buildings may be considered as a relatively high use, since most of these plants are too small for the installation of mechanical stokers and the labor of firing coal by hand is eliminated.

The advantage which Mexican oil enjoys in the New England States in competition with coal, owing to the facility with which it may be produced and transported, has already been mentioned. The city of Providence, R. I., is becoming an important distributing center and oil is coming into general use for heating the larger buildings.

The installation of oil-burning equipment and the supplying of fuel oil is a business requiring an organization with engineering, manufacturing and distributing departments, operating in a definite territory where tank wagons can be used for supplying customers. Companies of this kind are developing this business in Providence, Boston and other cities. The oil supplied is of about 16°Be. gravity, and mechanical types of burners are used in the smaller installations, with electricity as motive power for atomizing.* In larger installations steam is used for atomizing the oil. Fuel oil is extensively used for heating buildings in Pacific coast cities and in the southwestern States.

Colloidal fuel should be applicable for heating buildings, as it may be handled like oil. It is heavier than water and can therefore be quenched in case of fire by flooding the surface with water. This is an important advantage as regards insurance against fire.

Trent amalgam (pages 479 and 628) may be utilized with similar advantages and may be burned on grates without leaving ash to be removed from the furnace. This fuel may be fired mechanically without as continuous attention as is sometimes required for burning oil or pulverized coal where the electric power supply is subject to occasional interruptions. The elimination or reduction of the handling and disposal of the ash will be a considerable economy in city plants.

Pulverized coal has been used to a limited extent in Seattle, Wash., and has been distributed in tank wagons. Another possibility is the pneumatic firing of granulated fuel over a grate and this will be discussed in Chapter VIII. This may prove to be an excellent way of firing solid fuels automatically, in building-heating plants, when oil is less available. The business could be organized in the same way as has been done in connection with the application and supply of fuel oil.

TRANSPORTATION AND UTILIZATION OF COAL FOR CENTRAL POWER AND HEATING PLANTS

The dominant use of coal for the generation of primary power, with which may be included its use in central heating, gas and by-product plants, renders its efficient transportation and utilization in central stations a problem of fundamental importance.

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* Credit for information: Petroleum Heat and Power Co., Boston, Mass.

Transportation.—The predominant use of rail transportation for the coal supply is one of the weak links in the chain of movements by which energy progresses from the coal mine to the ultimate consumers of power and heat. Next to the mining of the coal, its transportation by rail involves human guidance to a greater extent than any subsequent movements, except where the coal is delivered by truck and fired by hand. The modern power station and its electrical distribution system are largely automatic in that the guidance of relatively few men is required for controlling a large amount of energy. The same may be said as regards a modern gas plant and its distribution system. While a long coal train requires only a small crew, the building, maintenance and operation of a railway system requires a large number of men. Also, the transportation of coal by rail involves the consumption of a large amount of coal by the locomotives.

The total tonnage of anthracite and bituminous coal shipped by railroads in 1916 was 490,077,529 tons. Some of this was consumed by the railways on which the tonnage originated. The remainder (for the year ending June 30, 1916) represented 33.5 per cent. of the total revenue freight tonnage* of all the railways (anthracite; 5.8 per cent and bituminous, 27.7 per cent). The proportion of the coal consumed by the railways in 1916, which is chargeable to the transportation of coal, has been estimated at 35,100,000 tons, or 7.16 per cent of the total tonnage of coal hauled.†

Our railway facilities have not been expanded to keep pace with the industrial growth of the country and are now overcrowded. This situation may be relieved in the following ways:

1. The improvement of our railway facilities by:
    (*a*) Additional tracks and rolling stock.
    (*b*) Larger freight yards and terminal facilities at congested points.
    (*c*) Electrification of lines carrying sufficiently dense traffic.
2. The diversion of part of the coal traffic to other channels, such as:
    (*a*) Waterways.
    (*b*) Gas-pipe lines.
    (*c*) Electrical transmission lines.
3. Economic fuel utilization.

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* *Annual Report*, I. C. C., p. 43.

† *Memorandum* by Division of Power Resources, *U. S. Geol. Surv.*

4. Intensive cultivation of food crops near centers of population. This can be greatly facilitated by the use of fertilizers, including nitrogen compounds obtained as by-products from the utilization of coal for generating heat and power. The inefficient utilization of agricultural lands in the more densely populated parts of the country makes it necessary to haul much food from distant regions (see Chapter VI).

Waterways.—From the viewpoint of transportation, coal is a low-grade commodity like ore, stone, sand, gravel and grain. Such commodities can be handled in bulk and can be shipped more economically by water. The further use of our available waterways will free our railways of a part of the burden of coal transportation and leave them available for carrying high-grade freight.

The New York State barge canal is a prominent instance where a splendid waterway is available for carrying coal as soon as boats, and facilities for loading and unloading them, are provided. Branch canals have been built connecting it with Cayuga and Seneca Lakes for the express purpose of loading coal, from the mines in Pennsylvania, at Ithaca and Watkins for shipment to points in central and northern New York, Vermont and Canada.

The increased cost of rail transportation should render shipment by waterways more attractive. The government, through its control of freight rates, should encourage the establishment of rates for hauling coal from the mines to loading points on waterways, which will render the combined rail and water rates competitive with the through rates by rail.

The prevailing rates have been legalized and changes require approval by the Interstate Commerce Commission, as recently exemplified when the railways petitioned for permission to reduce the rate for carrying grain from Buffalo to the seaboard. Permission was granted, enabling the establishment of a combined rail and water rate from Duluth to New York which was enough below the all-rail rate to divert the traffic to the idle lake steamers and thereby relieve the car shortage. The rates for carrying coal for long distances by rail were established under former competitive conditions and they are usually proportionately lower than local rates for shorter hauls, such as those from the mines to new or undeveloped waterways.

Gas Pipe-lines.—The possibilities of gas pipe-lines, as a factor in fuel transportation, are well exemplified by the existing pipe lines carrying oil and natural gas. When coal-products plants are located near the mines, or are centralized for supplying a district of considerable size, pipe lines for the conveying and distribution of artificial gas should prove to be important links in the transportation chain. Their principle function would be the carrying of gas for industrial and domestic heating.

Retort gas or water-gas, or a mixture of the two, may be distributed (page 1010). An interesting possibility, in connection with the preparation and conveying of steam fuel, would be a water-gas made by an external heating process and at a low enough temperature to permit of the recovery of ammonia (pages 491 and 499). Such a gas would consist largely of CO_2 and hydrogen, but the former could be removed during compression, by solution in water or by liquefaction. The resulting hydrogen, being a gas of low density, might be piped at approximately double the velocities which are practicable with other gases and this would, in most cases, offset its greater volume; hydrogen has a calorific value of slightly more than 300 B.t.u. per cubic foot.

Natural gas pipe-lines are operated at pressures as high as 1,000 lb. per square inch, steel pipes being used with bolted gasket joints. The leakage is often a serious factor, sometimes as much as 50 per cent. of the gas being lost from long lines. Pipe-lines for artificial gas are being constructed with welded joints which can be made gastight.

Coal Pipe-lines.—Several suggestions have been made that coal may be carried to market in pipe-lines just as readily as sand and gravel are carried through pipes in suspension in water, in connection with hydraulic dredging. The weight of the material carried is often equal to the weight of water used.

One suggestion contemplates the transportation of commercial sizes of anthracite from Scranton to New York through two 14-in. pipe-lines. The difference in elevation is about 2,000 ft., which would reduce pumping to a minimum. A possible objection might be that the domestic sizes would be subjected to serious losses by attrition, with the formation of much sludge, as in coal-washing operations. The latter could be recovered by the Trent process (pages 479 and 628) and put to low uses, or made into briquets.

In the case of bituminous coal, such attrition as occurs would be less objectionable since the fines can be pulverized while still wet and then cleaned with oil by the Trent process. The sludge can also be recovered and cleaned similarly, and the resulting "amalgam" distilled at low temperature for the recovery of hydrocarbon products and the production of semi-coke.

The presence of fine coal in suspension should materially reduce the friction in the pipe by imparting something of the lubricating quality of graphite. At the same time, it would increase the specific gravity of the water and thereby increase its carrying power.

The method of transporting solid material in suspension in water, on a large scale and in continuous service, has been very thoroughly developed in connection with the hydraulic mining of phosphate rock in Florida. Vast deposits of this rock are located, for the most part, under water. The rotary cutter at the bottom of the suction pipe breaks the rock into jagged particles of all sizes, which are efficiently handled by the pumps and transported for considerable distances through the discharge pipe-line. The material handled includes: (1) the overburden, usually of sand or sandy clay and hardpan, the latter being reduced to a maximum size of 8 inches; and (2) the phosphate deposit consisting of pebbles from the size of a walnut down to a grain of sand. The specific gravity of the phosphate averages about the same as quartz (about 2.6) and the percentage of solids handled runs as high as 32 per cent. by volume. The loss due to friction in the pipe is about 15 per cent. greater than in the case of clear water.

The earliest proposal to pump coal in this manner was made by W. C. Andrews in the early '90s. He broadly patented the method of pumping coal through pipe-lines and made some experiments as to the practicability of his invention. His process was used to some extent in the anthracite coal regions for pumping the culm and waste back into the worked-out portions of the mine, filling them to prevent falling of the roof, and this was practiced for quite a number of years before the value of the finer sizes of coal was demonstrated. At the present time suction dredges are working in the rivers in the anthracite region, removing the fine coal which has been wasted into the bed of the river.

This method has also been in successful operation for several years in England, over a distance of about half a mile. A greater distance involves no new elements, as it would be necessary to locate electrically operated relay pumping stations at quite frequent intervals. One plan, which has been worked out in considerable detail, calls for a 14-inch pipe with pumping stations spaced about every one and a half miles in level country. An electric-power transmission line would parallel the pipe-line and operate the pumps.

One of the difficulties which has been suggested is that the water will take up sulphur compounds in solution and that these will corrode the pipe and pumps. It has been determined by experiment, however, that corrosive action may be prevented by the introduction of lime, or other acid-neutralizing substance, at the sending end. It has been estimated that coal can be transported through pipe-lines for distances of from 130 to 320 miles at a considerably lower cost than by rail, provided the service is reasonably continuous. This, of course, requires the handling of a large tonnage throughout the year.

Electric-power Transmission.—The possibilities of electric-power transmission are so well exemplified by existing systems as to require but little comment. While a part of the power supply for a transmission network may be transmitted from distant mines or waterpowers, continuity of service may be rendered surer by supplying part of the power from central stations located near the main centers of consumption of energy. The interconnection of several types of generating stations and consuming industries increases the diversity factors of the power supply and of the load. The occurrence of the peak loads in different industries does not coincide in time and a smaller total generating capacity can supply the power and lighting requirements of a considerable territory, through an interconnected network of transmission systems, than if each industry generates its own power supply. The more diversified the character of the load, the higher will be the system load factor and the lower the cost of the service.

Both transmission lines and pipe-lines can be utilized most economically for supplying the base loads where the service is fairly continuous, while the peak loads, or seasonal loads, can often be more economically carried by plants located near the points of consumption. Better continuity of service is assured by this division.

The most favorable conditions under which power plants can be located at the mines are as follows:

1. Ample supply of condensing water. Large power stations must usually be located on a river or lake.

2. Where the distance from the markets will not require excessively long transmission or pipe-lines.
3. Where the existing transportation facilities are insufficient.

In the case of the northern Appalachian coal-fields, such conditions may be found on the western side of the Alleghenies more frequently than on the eastern side, where large rivers are lacking. Moreover, some of the railways which carry coal eastward were built for this traffic and carry but little other freight. Congested traffic conditions are encountered more frequently at a distance from the mines and nearer the points of consumption.

While relatively small power stations may sometimes be located on rivers in the mining regions, it is generally necessary to dam the river and run most of the water through the condensers. In such a station the coal may be utilized on a multiple-product basis to good advantage. When the cost of long distance transmission lines is taken into consideration, some of the advantages of burning the coal at the mines are offset and it becomes evident that economic transportation of the coal is more desirable for carrying large concentrated loads.

The large power stations contemplated in connection with the plans of the Super-power Survey, for supplying the base load in the territory between New Hampshire and the Potomac river, will probably be located on tide water, where ample condensing water is available and where coal can be received by water from Hampton Roads, Va. Economic rail transportation would be organized from the Appalachian coal-fields to that port.

There is another important factor to be taken into consideration which, in the future, is likely to assume controlling weight in connection with the location of base load stations; and this is the utilization of the waste heat. In the most efficient modern power stations over 80 per cent of the head generated in burning coal is rejected in the form of low-temperature heat. By sacrificing a part of the energy available for generating power, and burning more coal to offset this loss, steam may be rejected at a higher temperature and utilized for heating and manufacturing purposes within a limited radius from the station (see pages 298, 326 and 327). With the development of binary vapor turbines this may be accomplished without a reduction in the power obtainable from a ton of coal, as compared with present practice. In either case, the additional coal consumed in the power station will be very much less than would be required to operate these industries independently.

In order to bring this about, it will be essential to locate base-load stations near large centers of population, rather than near the coal mines. The availability of water transportation will also facilitate the delivery of raw materials and the distribution of the products. One industry wherein exhaust steam is extensively used is the manufacture of paper. With the impending exhaustion of the forests upon which a large part of our present paper mills are dependent for raw material, it will be necessary to establish a new pulp industry in Alaska. The U. S. Forest Service has collected data which indicate that the government forest reserves on the coast of southeastern Alaska contain sufficient pulpwood to support a large permanent industry, when the reproduction of the forests is given adequate attention. Water-power is also abundant. The pressed pulp can be shipped through the Panama Canal to the north Atlantic ports and then used for the manufacture of paper with the aid of exhaust steam. The use of exhaust steam for process heating is rapidly increasing as the economies which may be effected become appreciated in various industries. It is often more economical for established industries to generate a considerable part of their own power as a by-product of the steam required for process heating and for heating buildings, rather than to purchase central-station power exclusively.

The location of plants for extracting by-products from coal is discussed at the end of Chapter VII.

Economic Fuel Utilization in Central Stations.—The leading factors for consideration may be itemized as follows:

1. The utilization of local resources of low-grade fuel in territory now dependent upon the transportation of high-grade coal from distant sources.
2. The utilization of fuels on a multiple-product basis, including the use of waste products.
3. The use of efficient methods for burning fuels and for applying the heat generated.
4. Improvements in the efficiency of prime movers.
5. Concentration of the production of power from fuel in central stations where the most economical methods may be utilized, and its distribution electrically to consumers, including the railroads.
6. The use of electric vehicles, charged by central-station power, to help relieve the great demand for gasoline for urban transportation, and to improve the central station load factor.

These factors will be considered in order.

1. The Utilization of Low-grade Fuels.—With the present limited development of our waterpowers and of our deposits of low-grade fuel, the country is largely dependent upon localized mining activity in the regions where deposits of high-grade coal and oil are found. Large sections of the country receive their fuel supplies by long rail or water routes. They are often subject to delays from shortage of cars, locomotives, or shipping; from congestion of traffic or from transportation or miners' strikes. The cost of freight prohibits the transportation of any but the highest grades of coal for distant consumption. In such parts of the country there are undeveloped deposits of low-grade fuel which can be used locally by several available methods.

2. The Utilization of Fuels on a Multiple-product Basis.—At the present time the only processes in general commercial use for recovering by-products from coal are those used in the gas and coke industries, where coal is distilled at a high temperature and the residual coke, generally speaking, is not suitable for power generation, as it is a refined fuel made for special purposes for which it can command a higher price. The efficiency with which raw coal of high grades, as well as some fuels of lower grades, are burned on modern types of mechanical stokers renders the generation of steam a low use for prepared fuels. Therefore, only the less refined types are applicable, and the substitution of prepared fuels is dependent upon certain favorable economic factors:

(*a*) When the fuel is a residual product from a refining process, by which other more valuable products are recovered.

The more important examples are:

- Crude prepared fuels:
  - Coke breeze (from high-temperature distillation).
  - Semi-coke (from low-temperature distillation).
- Refined fuels:
  - By-product producer gas.
  - Pulverized semi-coke.

(*b*) When the fuel is prepared from by-products of mining operations, where the main product is a more valuable class of fuel, as:

- Producer gas.
- Pulverized fuel.

(*c*) Waste products from other industries, as:

- Blast-furnace gas.
- Producer gas (from vegetable materials).
- Hot-flue gas (from industrial furnaces).

The last source of heat is utilized for generating steam in waste-heat boilers in connection with furnaces, kilns and water-gas and producer-gas plants. Vegetable materials gasified include waste wood, sawdust and straw.

3. The Efficient Combustion of Fuels.—Fuels are burned with the maximum efficiency and facility in fluid or mobile form:

(*a*) Gaseous, liquid and pulverized fuels can be burned in furnaces which contain no grates or stoking machinery.

(*b*) Smokeless combustion may be maintained with a minimum percentage of excess air.

(*c*) The flexibility of control of the fire is an important advantage. Boilers may be forced to a maximum extent, or the fire may be extinguished instantly.

(*d*) Stand-by losses are reduced to a minimum. This is a very important economic advantage in the case of boilers which are operated intermittently, but which must be kept warm and ready for service. A cold boiler can be brought up to full steam pressure as rapidly as is consistent with safety.

(*e*) Fluid or mobile fuels may be conveyed, distributed and fired with pipes and simple equipment, and cleanliness may be maintained in the boiler room.

(*f*) No ash is formed in burning gaseous or liquid fuels. With pulverized fuel the ash and slag are readily removed, and the percentage of combustible remaining in the ash is insignificant. Fuels with a high-ash content are readily burned in suspension.

(*g*) Carbonized fuels and some classes of low-grade raw fuels may be burned in pulverized form more readily than on grates or stokers. Bulky fuels, such as these, require more grate area than high-grade coal.

(*h*) Pulverized fuel should be especially advantageous in steam plants used as reserves in connection with water-power systems, owing to factors (*c*) and (*d*).

(*i*) By-product producer gas is especially applicable for carrying the base load in fuel power systems, where the gas plant can be kept in continuous operation, and thereby earn the fixed charges on the investment. Fuels rich in nitrogen may be selected for this part of the service.

(*j*) In such systems the peak loads should be carried with coal, which can be more readily stored than gas. The coal-fired boilers will all be subject to intermittent operation and pulverized coal will have a more decided advantage over stokers than in systems where the entire load is carried with coal.

(*k*) Where high-volatile coal is used, hydrocarbon by-products may be extracted, in advance, by subjecting either or both classes of fuel to distillation at low temperature. The classification is that referred to under (*i*) and would be based on the nitrogen content, fuels lean in nitrogen being utilized for peak-load service.

(*l*) Where gas and coal are used in the same power system, they can be utilized in connection with separate stations, if desirable. When used in the same station, they can be burned under separate boilers. If the solid fuel is pulverized, they may be burned simultaneously, under the same boiler, with better efficiency than where lump coal and gas are burned together.

4. Prime Movers.—In past years the gas producer and gas engine have been widely advocated as the most efficient combination for the production of power from solid fuel. In 1916, the committee on prime movers of the National Electric Light Association reported as follows on the status of gas engine, and producers:

> "The large gas engine continues to lose ground as a prime mover for central-station work. At the present time gas engines are not being installed except where local conditions are particularly favorable to their use.
>
> "In the majority of localities where steam coal can be purchased at reasonable cost, the large gas engine cannot compete with the modern steam turbine, in spite of its low fuel economies. The steam turbine, combined with the steam-generating equipment, has made such rapid advances in the last few years in generating capacity per unit and simplicity of installation, that the fixed charges on steam installations have been very materially reduced. These low fixed charges of the steam plant are so much below the fixed charges on a gas-engine installation that they more than counterbalance any operating economies obtained from the generation of gas power.
>
> "Where, however, an abundant supply of natural gas, by-product coke-oven gas, or blast-furnace gas is available at an extremely low cost, and in those sections of the country where the price of steam coal is prohibitive, installations of gas engines are still attractive.
>
> "The development and adoption of the gas producer as a method of utilizing solid fuels for power purposes has been a disappointment in many respects. The anthracite and lignite producers have been successfully developed and are installed in those localities where such fuels are available at reasonable cost. The bituminous producer, however, has made practically no advance. This is due to the fact that the recent development in steam-boiler construction has given the boiler similar advantages over the producer that the steam turbine possesses over the gas engine. These advantages are: large capacity per unit, low first-cost, simplicity and flexibility of operation, ability to carry high overloads for an extended period of time, and low labor cost."

Even this report does not put the case quite strongly enough. Central stations in several Texas cities burn natural gas under boilers, which supply steam to turbines, in preference to using gas engines. A public service company, operating several of these stations, sometimes installs a single gas engine unit in a new town, owing to its mobility. As soon as the load becomes too large for this unit, it is replaced by steam equipment and the gas engine is moved to a new locality.

A number of large gas-engine electric plants were installed in steel mills, several years ago, and are operating on blast-furnace gas. Since then, however, it has usually been the practice to install steam plants and burn the gas under the boilers, except in the case of a few steel companies which prefer gas engines. The larger gas engines used are of about 4,000 kw. capacity and the multiplication of units, necessary for generating any considerable amount of power, makes the installation expensive and spreads it over a large area of floor space.

We shall take as an example a blast-furnace plant with a blowing plant for furnishing the air blast and a steel mill for finishing the product. On the average, the blast furnaces will furnish enough gas for preheating the blast air in the stoves and for generating steam for operating turbines, both for driving centrifugal compressors for furnishing the blast and for generating the electric power needed in the steel mill.

Blast-furnace gas, however, is a by-product from a furnace which primarily produces pig iron and the quality cannot always be maintained for fuel purposes. Also, the power load is variable and the peaks are considerably in excess of the quantity of gas available. It is necessary, therefore, to use a certain proportion of coal, or coke breeze, as a supplementary fuel for maintaining the steam supply. This is usually burned on grates and fired by hand, while the gas is burned above the grates in the same furnaces. This combination is not very efficient, and a more recent practice is to burn the gas and coal under separate boilers and use mechanical stokers for the coal.

A new blast-furnace plant and power station have recently been built by the Ford Motor Co., at Detroit, in which pulverized coal will be burned simultaneously with blast-furnace gas in the same boiler furnaces. It is expected that a better efficiency will be maintained with the mixed fuels than is possible where blast-furnace gas is burned alone. This installation will be further described in Chap. VIII.

When gas engines are used for generating power and furnishing the air blast, the thermal efficiency is slightly higher, so that very little coal is required for carrying the peak loads. When the gas becomes poor, however, it is necessary to burn coal in auxiliary gas producers. On Sundays, and at other periods when the power load is light, there is a considerable amount of surplus gas available which is allowed to go to waste, and this partially offsets the better efficiency of the gas engines.

The relative initial costs of the two types of plant may range from 180 to 300 per cent. for the gas-engine plant, as against 100 per cent. for the steam-turbine plant, while the fixed and operating charges for the gas plant may exceed those of the steam plant by 40 or 45 per cent., the extra coal being included in each case.* It will be seen, therefore, that the use of pulverized coal overcomes one of the few weak points in steam-turbine plants for blast-furnace and steel-mill service. The use of coal pulverized in the same milling plant, for steel furnaces, has already been mentioned.

The steam boiler has a considerable capacity for storing energy which may be drawn upon for carrying sudden peak loads of short duration, such as are of frequent occurrence in rolling-mill service. The use of pulverized coal will still further augment the capacity of the steam plant for carrying such loads. The gas-engine plant, on the other hand, lacks this inherent overload capacity and must depend upon the availability of surplus gas when needed, and perhaps allow gas to go to waste in the intervals between peak loads.

New Types of Internal Combustion Engines.—Among the various modified forms of large gas engines that have been devised, probably the most meritorious are two which originated in England. One of these, the "Still engine," is double-acting, steam being used in the end of the cylinder nearest the connecting rod, and is generated in a waste-heat boiler from the hot exhaust gases.†

The other is the "Humphrey pump," in which a large column of water surges back and forth in an inverted siphon, one end acting as a liquid piston in the closed end of the pipe. This has been developed as a very economical gas pump or air compressor.‡

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* Consult: "Blast-furnace and Steel-mill Power Plants," by R. H. Rice and S. A. Moss, *Proc. Eng. Soc. of Western Pa.*, **33**, 81–130 (1916). Also, "Recent Installations of Large Turbo-generators," by R. H. Rice, *Am. Iron & Steel Inst.*, May 25, **1917**.

† Consult pages 387 to 391. Bonecourt waste-heat boilers are used on gas-engine exhaust.

‡ A number of articles describing the Humphrey have been published in *Engineering* (London), including the following: **94** (1912), 799; **95** (1913), 708; **96** (1913), 835; and **111** (1921); 157 and 232.

There is a possible future application for the gas pump, in connection with hydro-electric plants, as a simple form of fuel-power reserve unit. During periods of low water, it could be used to pump water from the tail-race back into the head bay.

There have been many suggestions made for burning pulverized fuel in internal combustion engines, but the ash problem makes the solid-piston type of engine look rather unpromising. The use of pulverized fuel in the liquid-piston type, however, may be a simpler problem, especially in the case of pulverized charcoal, peat or lignite. These fuels ignite readily and may be obtained with a low-ash content. Pulverized fuel should be especially advantageous in connection with water-power reserve units.

The Possibilities of the Turbine.—Since the first Curtis turbines were placed in operation in 1903, the capacity of the largest units have been increased from 5,000 kw. to 45,000 and the steam consumption has been reduced to less than one-half of that of the original machines. The efficiency of the turbine generator unit has been increased from 47 or 48 per cent in 1903 to 75 or 78 per cent in 1920. The balance of the increase in steam economy is due to increased thermal range in the steam cycle; higher steam pressure, superheat and vacuum being used. The temperature of the exhaust is limited by the temperature of the cooling water and by the temperature gradient in the metal of the condenser tubes. The latter factor is about 30°F. (17°C.). The steam pressure at the turbine remained at a maximum value of about 200 lb. per square inch (15 kg. per sq. cm., abs.) for a number of years, and the steam was often superheated to a temperature of 550 or 600°F. (288° to 351°C.).

Future possibilities for increased efficiency lie in further increases in the upper limit of the thermal range:

(*a*) By operating with increased steam pressures and superheats with a single turbine.

(*b*) By operating high-pressure and low-pressure turbines in series and re-superheating the steam between the two units.

(*c*) By using a binary vapor cycle with separate turbines operated by the vapors of two substances which boil at quite different temperatures, such as, mercury vapor and steam; the heat of condensation of the mercury vapor being used to generate steam in a condenser boiler.

(*d*) By the development of an efficient gas turbine. No machine of this type, however, has as yet developed a high efficiency.

The possibilities of cycles (*a*), (*b*) and (*c*) are summarized in Table XXXIII. The highest steam pressures in commercial use in the United States range from 250 to 300 lb. (18.5 to 22 kg. per sq. cm., abs.) at the turbine, while the steam is superheated to temperatures of from 622° to 689°F. (328° to 365°C.). These pressures and temperatures, however, have only recently come into use in a few stations. At Joliet, Ill., the Public Service Corporation of Northern Illinois is generating steam under a pressure of 350 lb. (2.55 kg., abs.) at the boiler. This pressure is reduced to 300 lb. (22 kg., abs.), at the turbine while being superheated to 622°F. (328°C.). A turbine has been operated at 350 lb. pressure for several years at the works of the British Thomson-Houston Co., Rugby, England. A new station is being built at Manchester, England, which will generate steam at 375 lb. (28.3 kg., abs.) and this will reach the turbine at 350 lb. and with a temperature of 750°F. (34.3 kg., abs.). This station will probably use as high a pressure as can be efficiently utilized in a single turbine, owing to the increasing percentage of condensation during the expansion of steam from higher pressures.

A new station has recently been put in service at North Tees, Middlesboro, England, in which the steam is generated at 475 lb. (34.3 kg., abs.) and reaches the turbine at 450 lb. (32.6 kg., abs.) pressure, with a temperature of 700°F. (371°C.). The turbine is divided into two units which operate in series, the steam being re-superheated before use in the low-pressure turbine, to minimize condensation. In both the Manchester and Middlesboro stations, the combustion air is preheated about 200°F. (110°C.), by heat from the flue gases, in large preheaters. This is a new departure in power-station practice.

The limiting theoretical efficiencies which may be approached in steam-turbine plants, when operating at various steam pressures, are indicated by the curves in Fig. 76. These have been calculated on the basis of the Clausius or Rankine cycle. The lower curve, indicated by a full line, is calculated from the tables of Marks and Davis and of Greene; the specific heat of the steam at constant pressure (C_p) being taken from the latter authority. It indicates the efficiencies corresponding to an initial temperature of 600°F. (315°C.) and a final pressure of 1 inch of mercury, absolute. The broken line just above is calculated from Goodenough's steam tables and is for the same initial and final conditions. The upper curve is also from Goodenough and is calculated for an initial temperature of 671°F. (355°C.). In all cases the temperature of the feed water is taken as 79°F. (26°C.), corresponding to a final pressure of 1 inch of mercury.

The Rankine cycle efficiency is the *ratio* of the available energy (between the initial and final conditions) to the total heat required to raise the liquid from the final temperature to the boiling-point to vaporize it and to superheat the vapor to the initial temperature.

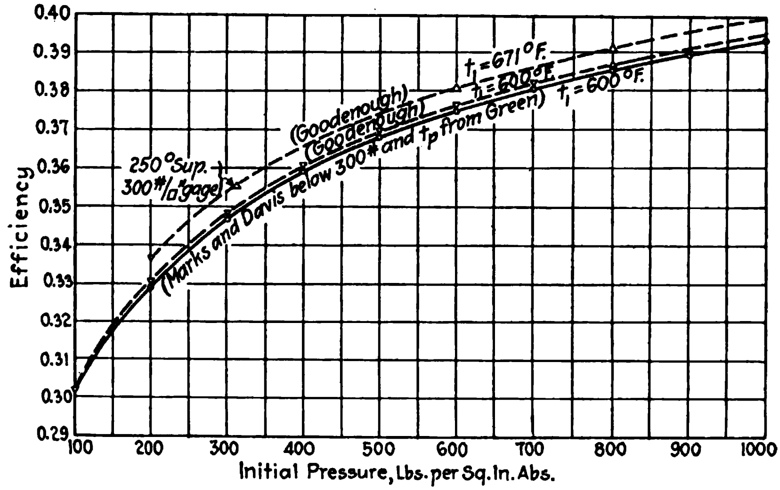

Fig. 76.—Rankine cycle efficiencies for various initial pressures and final pressure of 1 in. of mercury.

The practical application of the Rankine cycle is represented by the case where the feed water is heated entirely by the sensible heat of the flue gases in "economizers" and "feed water heaters." At a pressure of 215 lbs. (15 kg.) absolute, with an initial temperature of 600°F. (315°C.), the limiting theoretical efficiency (according to Goodenough) is 0.333. At a pressure of 1,000 lbs. (70 kgs.) abs., and an initial temperature of 671°F. (355°C.), the limiting efficiency is 0.399—an increase of 20 per cent. The first case represents a common practice at the present time, while the second case represents the highest pressure which would be at all likely to be practicable in the future. The actual efficiencies attainable in either case differ from the limiting efficiencies by the amount of the thermal and mechanical losses, and their proportion will presumably increase with the higher temperatures and pressures.

The Rankine cycle efficiency is lower than that of the Carnot cycle and this difference becomes greater as the steam pressure increases. Many of the more modern stations operate on a cycle which is intermediate between the Carnot and Rankine cycles. It differs from the latter in the fact that the feed water is heated regeneratively, in part at least. This is accomplished by the use of exhaust steam from the auxiliaries or by bleeding steam from the main units before it has completed its expansion. The use of such intermediate cycles makes it possible to offset some of the losses which detract, in practice, from the theoretical thermal efficiency.

The maximum practicable operating pressure remains to be determined, but it will doubtless lie somewhere between the pressures of 600 (42 kg.) and 1,000 lbs. per sq. in. (70 kg.). The possible gain in efficiency is important in the case of base-load service, where the saving in fuel should more than offset the fixed charges incident to the additional investment required.

When operating over a large temperature range with a single vapor, pressure limitations are soon reached, and, in the case of steam, the low density and high-latent heat of vaporization give rise to high spouting velocities. This necessitates a large number of stages in the turbine to secure good efficiency.

Higher efficiencies may be more readily obtained by using two vapors in series, such as mercury and steam. Mercury vapor has a much greater density than steam and a lower heat of vaporization; hence the spouting velocity is low and it may be used in a high-temperature turbine of very simple design. A mercury turbine and boiler are being developed by the General Electric Co. under the direction of W. L. R. Emmet, who has supervised many of the initial steps in the development of the Curtis steam turbines built by this Company. The first large experimental unit has been operated for several weeks at loads up to 1,000 kw. on the mercury turbine. This problem is receiving intensive study at the present time and gives promise of practical results in the way of a successful prime mover with an efficiency comparable with that of the Diesel engine.

Moreover, this high efficiency may be attained with solid fuels, whereas the Diesel engine is limited to oil. The fuel will be burned, by any standard method, in the furnace of the mercury boiler. In central stations, the present steam turbines can be used and only the boilers need be removed and replaced by the mercury equipment.

The 1,000 kw. experimental unit has been operated under conditions which are equivalent to a coal consumption of about 11,300 B.t.u. (4,500 cal.) per kilowatt hour, assuming that the steam produced is used as efficiently as in the best power stations. A consumption of 18,000 B.t.u. (7,140 cal.) is considered extremely good economy in large steam stations at the present time. In the tests mentioned, the mercury vapor was generated under 11 pounds gage pressure (1.77 kg., abs.). A smaller mercury boiler of improved design has been operated under pressures up to 35 lbs. gage (3.67 kg., abs.), which should give a higher efficiency.

5. The Concentration of the Generation of Power and Heat in Central Stations.—We have seen how coal is used inefficiently in small plants in any industry and that the maximum economy is only possible in large prime movers of modern design. The usual practice in large central stations is to use the most efficient units for carrying the base load and to keep them in fairly continous operation at their most efficient loading. This leaves the peak loads, which are of shorter duration, to be carried by the order units. The methods for utilizing prepared fuels will fit in well with this practice. Equally good results may be attained by concentrating both the isolated plant loads and the railway load in large central stations, and the diversity factor, in the time of peak loads in different industries, will improve the load factor of the power system.

The use of more efficient prime movers should enhance the economic value of utilizing the exhaust steam from turbines for the distribution of steam or hot water for heating purposes within an economical radius from the power station. Turbines can be operated non-condensing, to obtain exhaust steam for heating; and the greater the thermal range above the temperature of the exhaust, the greater will be the ratio of the main product—electricity—to the by-product—heat.

A possibility of considerable interest in this connection, is the location of manufacturing industries in a zone about a power station where steam can be distributed and used for manufacturing purposes throughout the year, as well as for heating buildings in winter. The concentration of power and heating loads in one central station will render possible the use of fuel with a maximum efficiency, a greater part of the high temperature heat being utilized in high efficiency prime movers than has been possible heretofore.

The same considerations apply in the case of isolated industries using large quantities of steam for process heating or for heating buildings. A large part of their power supply can be most efficiently obtained as a by-product when the generation of heat and power is concentrated in one station.

6. Improving the Load Factor.—Central stations are usually lightly loaded during the latter part of the night and current can be sold at reduced rates for charging storage batteries. This will improve the load factor and increase the base load, thus making it possible to operate the more efficient units for longer periods or to install more of them.

The principal application for storage batteries is for electric vehicles, and especially for commercial vehicles for city and suburban use, within the limits of a 30-mile daily service. The more extended use of electric vehicles will conserve gasoline and will transfer this demand for fuel to our coal and water-power resources. It will also replace horses and release farm land for raising food which is now required for horse fodder (see pages 267 to 290).

CONCLUSIONS

The problems which have been reviewed are major problems, some of which require the use of large amounts of capital to effect improvements. Referring to page 291, the tabulated alternatives represent the available means by which the country's fuel and transportation problems can be bettered. If recent advances in engineering are neglected by those who wish to improve existing transportation conditions, and the available capital is utilized in merely enlarging our present railway facilities along the lines of steam operation, the capital so used will not have been invested in a constructive way.

During the past 15 years, or more, the development of our railway facilities has been constantly hindered: first, by popular and governmental obstruction which interfered with the financing of extensions and equipment; secondly, by financial depressions; and, thirdly, by the war. Consequently, our transportation facilities have not kept pace with the growth of the country's industries or population. This condition presents great opportunities for constructive work along all of the lines mentioned on page 310. The necessary betterment work should be sufficiently broad in its scope to make it unnecessary to increase continually our railway mileage in proportion to the growth of the country.

In other words, a good part of the available capital should be invested in the electrification of our existing railways and industries, and the most economical methods should be utilized in generating the necessary power. And, wherever it is practicable, the railways should be relieved of a part of the burden of fuel transportation.

CHAPTER VI

THE GASIFICATION OF FUELS

By

F. Parkman Coffin*

Gaseous fuels represent the most highly refined type of fuel available, owing to the facility and efficiency with which they may be distributed and applied, the ease of instantaneous control, the saving of labor, and cleanliness. The application of artificial gas is, however, often limited by the cost of manufacture to applications where raw fuels cannot be used to as good advantage.

Gas for Low Uses.—Good grades of coal can be burned in steam-power plants so efficiently, either on stokers or in pulverized form, that artificial gas can compete with raw coal only under relatively favorable conditions, as:

1. When made by the gasification of low-grade fuels which can be obtained at a relatively low cost and which cannot be as efficiently utilized in the raw state. These include colliery refuse and coals naturally high in ash or sulphur. Coals of the latter class are often left in the mines. Refuse includes pickings from the mines or preparation plants containing bony coal, rock or duff, as well as washery refuse and fine screenings. This refuse often contains a large percentage of combustible matter which may be recovered by burning the material in gas producers. It is often desirable, however, to clean the refuse by washing or other means before gasifying. Refuse material may be crushed to a finely divided state to facilitate further cleaning (page 608). Thus mine output may be graded into three major products:

(*a*) High-grade coal for shipment.
(*b*) Low-grade coal for local use.
(*c*) Tailings for mine filling.

2. When obtained as a by-product during the utilization of solid fuels for other purposes. Blast-furnace gas is a good ex-

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* Research Laboratory, General Electric Co., Schenectady, N. Y.

ample, as well as surplus gas from coal carbonizing plants located where there is no local market for gas for higher uses. This will be considered in Chap. VII.

3. When obtained as one of several main products during the complete gasification of raw fuels on a multiple-product basis. By-product producer gas, obtained with the recovery of ammonium sulphate, belongs in this class and will be considered first.

Gas for High Uses.—Gaseous fuels can be manufactured for low uses by processes which involve considerable dilution with inert constituents. If gas is to be transported or distributed through pipes for any considerable distances, however, it must be made by processes which will exclude air from the retorts and thereby produce a richer gas. The heat required for gasification may be generated either internally or externally.

1. Internal heating is exemplified in the manufacture of water gas by alternate blasting with air and steam. This is usually made from expensive fuels, like coke or anthracite, and then enriched with an expensive oil. New types of generators may make it possible to use cheap fuels.

2. External heating is applicable to continuous processes for the gasification of pulverized fuel.

3. Hydrocarbon gases are obtained as one of the products of the distillation of coal. Coal gas is now used in undiluted form, but is rendered costly by the fixed charges resulting from the high initial cost of plant construction. It should be diluted with water gas made from cheap materials. In other words, coal gas should be used for enriching water gas in place of oil, as discussed in Chap. VII.

GAS PRODUCERS WITH BY-PRODUCT RECOVERY

History.[1]—The art of generating producer gas from coal is a very old one, but the development of the simultaneous recovery of the valuable by-products has been confined to the last 30 years or so. The earlier attempts are generally recognized to have been made in Great Britain. In that country, the knowledge that the treatment of fuel by a mixture of air and an excess of steam would convert a large percentage of the nitrogen content into ammonia, was first applied on a large scale. The details of a plant to operate on this principle had already been worked

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[1] Abstracted from "Gas Producers with By-product Recovery," by ARTHUR H. LYMN, *Trans. Am. Soc. Mech. Eng.*, **1915**, 1231.

out by Young and Beilby in England and by Grouven in Germany, and others.

The gas producer designed by Young and Beilby was externally heated. The coal was distilled in the upper part of the producer, or retort, and the tar vapors passed down through the red-hot coke, where, it was claimed, they were decomposed into permanent gas and ammonia. The coke in the lower half of the producer was burned in a mixture of steam and air. The gases from both the upper and lower zones passed out of the producer by way of exits at the middle. As far back as 1883, Young and Beilby claimed to recover in the form of ammonia from 60 to 70 per cent. of the total nitrogen in the fuel. Although their producer operated on a different principle from that used today, the comparison of their gas (Table XXXIII) with the gas which has since become so widely known as Mond gas, shows that it was of quite similar composition.

TABLE XXXIII.—COMPOSITION OF PRODUCER GAS

	Young & Beilby, 1883, per cent.	Mond gas, per cent.
CO_2	16.6	14 to 16
CO	8.1	10 to 12
CH_4	2.3	2 to 3
H_2	28.6	25 to 29
N_2	44.4	difference

The Mond Process.—Over 30 years ago Ludwig Mond first put into commercial practice the process described in his British Patents No. 3821 (1883) and No. 8973 (1885), for gasifying fuel by means of steam and air and simultaneously recovering the ammonia. His first plant was installed at the works of Brunner, Mond & Company, Northwich, England, and its capacity was developed to some 200 tons a day.

The Mond producer was rectangular in section and was formed with a kind of double chamber. Its operation was similar to that of Young and Beilby, in that distillation and gasification of the coke took place in the upper and lower chambers, respectively, and the mixed gases were drawn off at the middle. The gas was passed into a long horizontal rectangular washer and a fine spray of water was thrown into it by a series of revolving dashers. This removed a large proportion of the dust, which was afterwards taken out of the water lute manually with long scoops, an irksome operation. From the washer, the gas was conducted into a high

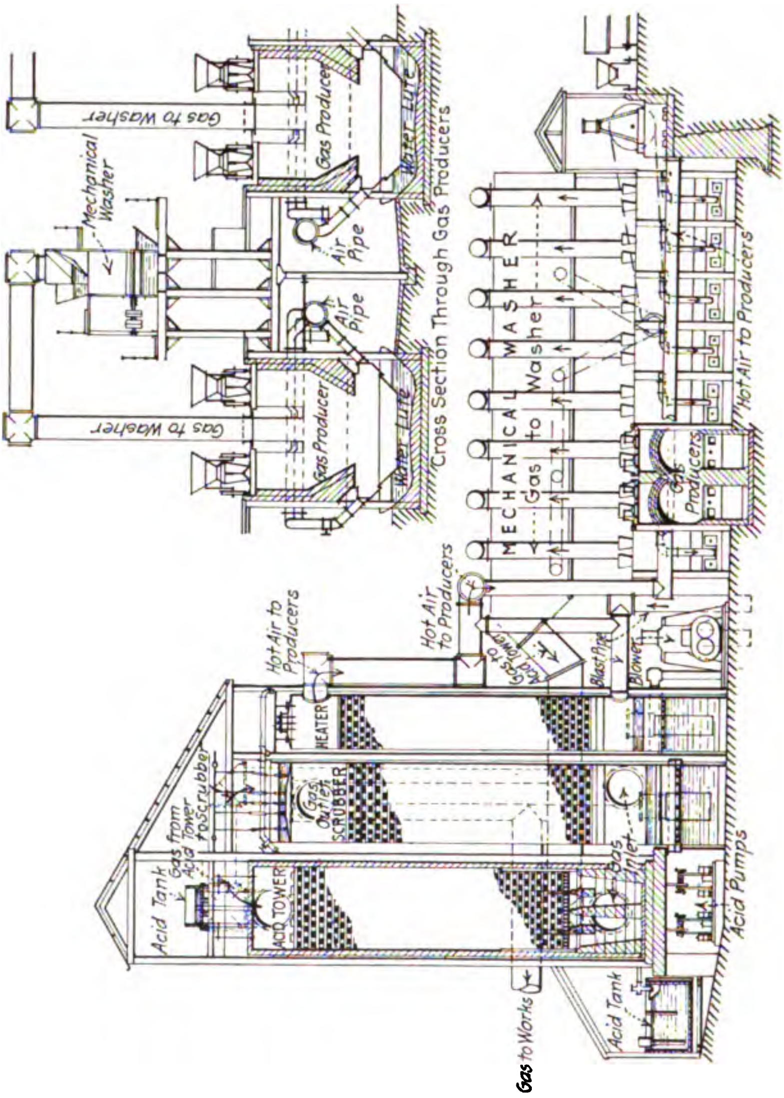

FIG. 77.—Mond system producer gas ammonia recovery plant.

lead-lined acid tower, filled with earthenware ring tiles, where, in passing upwards, it came into contact with a sulphate of ammonia solution trickling down (Fig. 77). This solution contained a slight excess of sulphuric acid which absorbed nearly all the ammonia contained in the gas. The gas then passed into a similar tower, called the scrubber, where it was brought into contact with cool water and was then delivered for use in a clean and cool condition.

The warm water from the scrubbing tower was collected in tanks and pumped to the top of a similar tower, called the heater. In this tower it was brought into contact with the incoming cool air on its way to the producers. This air was warmed to a temperature of 70 to 80°C. and saturated with water vapor. The water was used in a continuous cycle as a medium for heat transfer.

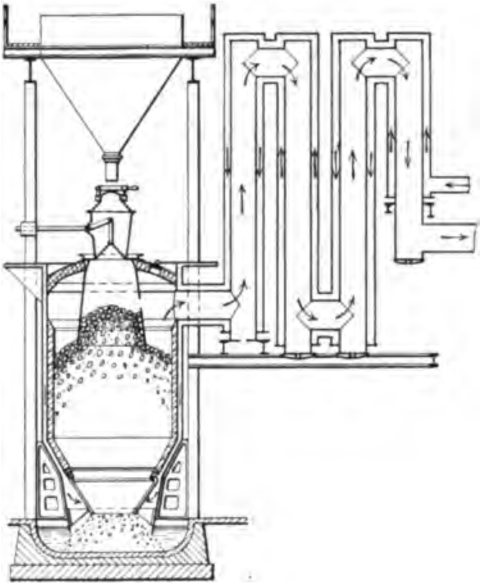

Fig. 78.—Mond producer with superheater.

After this plant had been in operation for some time, it was found that, owing to the large proportion of steam in the air blast, the heat value of the gas was below the desired standard and also the yield of ammonia was less than that which Mond had set out to obtain. It was therefore decided to change the design of the gas generating part of the plant so that the air and steam blast would enter the producer with a considerable degree of superheat, thus enabling a still greater excess of steam to be used. This modified design was disclosed in Mond's British Patent No. 12,440 (1893) and is shown in Fig. 78. The producer was made circular in section, instead of rectangular, and its whole shell was surrounded by a jacket through which the air was passed on its way to the grate, reducing the losses from radiation and at the same time further superheating the steam and air blast. Directly contiguous to the producer was arranged a superheater, consisting of a series of parallel tubes with alternate ends connected, surrounded by a series of larger tubes forming an annular space. The gas from the producer passed through the inner tubes and superheated the steam and air blast which was passed through the annular space in a counter-current direction on its way to the producer. With this provision, the gas was found to possess a much higher heat value and a considerably increased yield of ammonia was obtained without extra fuel.

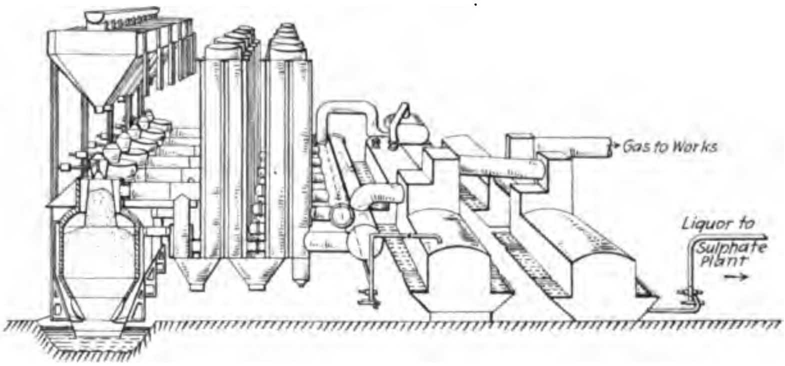

FIG. 79.—Mond type ammonia recovery plant with double chamber washers.

It is interesting to note that Mond, with that great courage in engineering undertakings for which he was famed in the days of his greatest activities, built a very large plant at the outset and smaller plants in later years. This was contrary to the usual order of things, and discloses the reason for the widespread idea that by-product producer plants were only profitable when built in very large and costly units.

Mond and his successor in England—the Power Gas Corporation—built many producer gas plants. Most of the larger plants were equipped for ammonia recovery, their capacity ranging from 10 to 250 tons of coal per day. The most interesting plant is the central station at Dudley Port, Staffordshire, for the distribution of Mond gas through 30 or 40 miles of pipe lines supplying an area of about 120 square miles. The gas from this station is supplied to iron and steel works, machine shops, foundries, galvanizing works, pumping stations, enameling works and municipal electric stations. The installation had originally a capacity of 16,000 hp. and this has since been largely increased. This plant is unique in that, it is the only central station in the world intended for the distribution of producer gas. Several years operation were required to demonstrate the advantage of producer gas service to the public and then the number of consumers increased rapidly.

Up to about the year 1897, Mond was constantly endeavoring to improve his process, but after that time he appeared to be satisfied with his design and in fact, in advancing years, he became adverse to any material modifications. The result was that the design of the Mond plants did not advance with the times and some authorities are of the opinion that, in those cases in America in which Mond system plants have not been so successful as was expected, it has been chiefly attributable to this factor and to the failure to realize that a certain state of reliability and efficiency in other countries, with quite different fuels and under totally unlike conditions, is not necessarily a criterion for exactly the same results in this country.

The Duff Process.—After Mond had demonstrated the success of his process, it was not long before another worker, E. J. Duff, claimed attention. As a whole, Duff's plant embodied very little to distinguish it from the Mond plant, the difference being mainly in the details of the construction of the superheater. Several large plants were constructed according to Duff's designs. Mond and Duff were at one time in conflict in the matter of their patents, but their interests were afterwards amalgamated into one company, The Power Gas Corporation, formed in 1901.

Modifications by Other Investigators.—Crossley Bros., of Manchester, were the next to claim material improvements, which, however, do not appear to have been realized in practice. The claims made for this plant were that the washing and cooling of the gases, as well as the condensing of the water vapor and the absorption of the ammonia, took place in one and the same apparatus, the ammonium sulphate liquor being utilized for the purpose of saturating the air with water vapor and the liquid being thereby cooled at the same time. As a matter of fact, in the first series of operations a washer made up of two compartments was used; the gas would leave this apparatus in a more or less uncooled state and also practically saturated with water vapor at a comparatively high temperature.

The second claim made, that is, that the air was saturated by means of the sulphate liquor, represented a very dangerous practice. A fine sulphate of ammonia liquor spray, with its excess of highly-corrosive acid, would naturally be carried forward to the superheaters, etc., and with very obvious results. Crossley Bros. took out later a patent for the utilization of the above system in combination with a somewhat costly bed of lime, which the saturated air had to pass through, clearly to absorb its contained acid spray.

Various modifications of ammonia recovery plants are also disclosed in patents issued to A. B. Duff, of Pittsburgh. Notable among these is a producer with a circular grate and also a circular section superheater with four enclosed gas tubes. In another design (British Patent No. 4,372 of 1910) Duff claims that, by passing the gas around the evaporator before entering the washers, its heat can be utilized for evaporating the sulphate of ammonia liquor. On first sight, this idea appears to be a good one, but great difficulty may be experienced in carrying it out in practice, on account of the dust and tar present in the gas at this stage of the operations. Moreover, in this design the gas is washed before it is allowed to enter the ammonia absorption tower, and the washing water is used for saturating the air going into the producers. It therefore appears that the air will carry to the producers a not inconsiderable proportion of the ammonia which will thus be lost.

Quintin Moore designed a producer divided into three parts, the lower one brick lined, the middle one water jacketed and the upper one air cooled. By this cooling of the upper part of the producer, Moore claimed to obtain a good yield of ammonia with about half the amount of steam in the air blast. It does not seem likely, however, that such cooling can penetrate far into the fuel bed, and it should not be overlooked that other workers, in particular Mond, previously considered the possibility of recovering ammonia by means of merely cooling the producer, but came to the conclusion (based on sound scientific knowledge) that cooling was not the only desideratum in ammonia recovery.

One can easily overrate, too, the importance of saving steam.

In the Mond process, practically all the steam is generated from waste heat and, moreover, most of it is continuously recovered. Any further saving can only be secured at the expense of some of the sulphate of ammonia yield.

Development of Mechanical Producers.—In the gas producer of an ammonia recovery plant, mechanical action which has been so widely applied to ordinary gas producers, both in the United States and in Germany but not so much in England, involves agitation in the fuel and ash zones of the producer and mechanical ash removal. Many attempts in this direction of mechanical action have been made and some of them have met with more or less success.

What was probably the first proposal was made by E. J. Duff, who designed an octagonal section revolvable producer with a stationary grate, ash trough and top (British Patent No. 15,646 of 1901). There is no record of any practical trial having been made of this producer.

The next proposal was made by Mond, who applied the well-known Talbot stirrer to one of his producers. It was tried out thoroughly with various coals of a more or less coking nature. It was very costly to install and its operation was not without difficulties.

A mechanical ash-removing apparatus, designed by Trump, has been adopted on a somewhat large scale. A battery of these so-called Mond-Trump producers was built in England. It was very costly and the information available concerning its operation has not been very encouraging.

A. B. Duff used a mechanically operated stirring poker with non-caking Scotch coals with good results. As these coals have worked well in stationary producers, however, the only advantage to be gained is an increased rate of gasification. A trial of this poker with caking coals would be of greater interest.

A. H. Lymn first tried using a revolving producer but without much success. The great depth of fuel requisite for ammonia recovery renders the operation of revolving shell producers exceedingly difficult. When using a caking coal, the producer shell revolved while the coal remained more or less stationary. This resulted only in the grinding of the coal at the periphery.

Lewis A. Riley, second, then designed, in cooperation with Lymn, a stationary shell producer with mechanical ash removal and also a mechanical agitating device operating in the top zone of the producer; all especially adapted to work with caking American coals. A complete by-product experimental plant was built on these designs by The Westmoreland Coal Co., at Irwin, Pa., and trials were conducted on a highly caking bituminous mine waste during the years 1914 to 1917. The results were satisfactory and that Company has built a commercial plant of about 120 tons capacity.

THE LYMN SYSTEM*

Arthur H. Lymn for some time had charge of the Mond gas central station at Dudley Port. While technical manager of the Power Gas Corporation, which built many other Mond gas plants, he made an initial step toward the simplification of the Mond system on the basis of his British Patent No. 8,014 (1908). This was an attempt to dispense entirely with the costly and irksome towers of the Mond and other plants, which became blocked up from time to time, causing serious trouble and delay. The attempt was made by replacing the mechanical washer and towers by washers of special construction, which could not become blocked up. Four double washers were proposed, one for washing the gas, the second for absorbing the ammonia, the third for cooling the gas and the fourth for saturating the air. This design was later modified in favor of a double-luted washer and was changed a third time by the Power Gas Corporation for a combination of double- and single-chamber washers upon the same principle. An idea of the general appearance of a plant with these washers may be obtained from Fig. 80.

About 1910, Lymn, having left the employ of the Power Gas Corporation, set out to design a new type of plant which should retain the advantages of previous types without their disadvantages. He was led to do this by the realization that, in spite of the cheapness of producer gas as made by plants operating under the Mond system, and although a considerable number of plants had been built and operated in a somewhat restricted number of countries, the adoption of the producer-gas process had not become general throughout the industrial world. Careful investi-

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* From information furnished by L. A. Riley, 2d, Licencee for the Mond and Lymn Systems in the United States. Also from "Lymn By-product Producer Gas Plant and the Utilization of Low Grade Fuels," *The Iron & Coal Trades Review*, March 8, 1918. Also, A. H. Lymn (*loc. cit.*, p. 330). See note on p. 364.

gations of the situation led to the conclusion that, although the process as such was, and is, really good, the means adopted for carrying it out left much to be desired, especially from the point of view of capital outlay, labor requirement, repair costs and simplicity of operation. These drawbacks were inherent primarily to the ammonia absorption, gas washing, gas cooling and air saturating elements to the plant. All these operations were heretofore carried out in high and cumbersome towers packed with earthenware ring tiles (Fig. 79), or in equally cumbersome horizontal luted dasher washers.

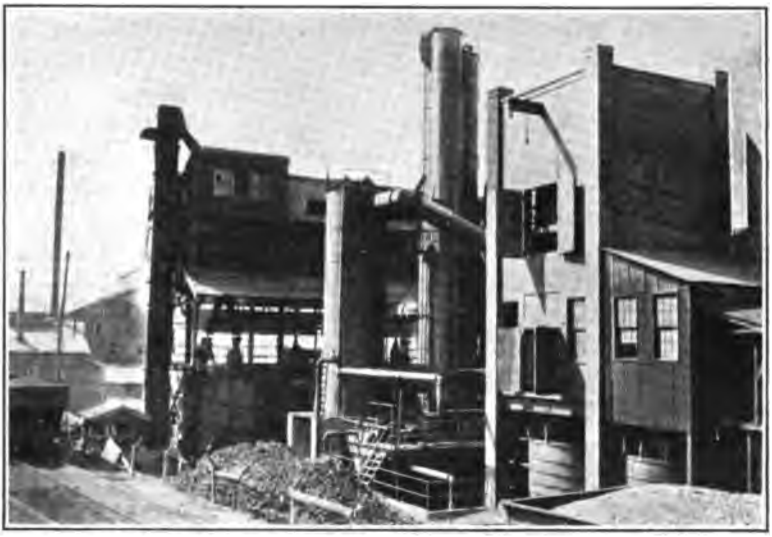

Fig. 80.—By-product producer installation at Fairmont, W. Va. This installation supplies gas for firing glass furnaces.

Vertical Static Washers.—A system of patented vertical washers, in which an intensive washing of the gases was brought about chiefly by means of the momentum of the gases, was first designed and put into practice. Vertical mechanical washers had not been used previously in gas-producer plants and Lymn first designed one on lines already known in other branches of the gas industry, in which the washing liquid was sprayed by means of a series of co-axial revolving discs upon collecting cones, each of which delivered the liquid directly upon the next revolving disc below, and so on. It was found, however, in setting this washer to work, that, with such an arrangement, the momentum of the gas was performing much more work than was the mechanical movement of the discs, a rather surprising fact. Accordingly, the mechanical feature of the washer was eliminated, the collecting cones were cut away to give the gas more play, and the washer now had the appearance as shown in Fig. 81. It will be seen that, if plumb lines are taken down the inside edges of the collecting cones and down the outside edges of the discs, a considerable space exists between them, which is such in practice that, if no gas is passing, the water entering at the top falls straight down to the bottom.

The apparatus consists of a vertical cylindrical chamber containing a series of inverted truncated cones. Through the center of the apparatus extends a shaft, to which is fixed a number of discs. The water entering at the top is distributed to the uppermost disc, from which it is driven by the gas on to the surrounding cone; thence to the next disc and next succeeding cone, and so on. The gas entering at the bottom passes up through the liquid sheets thus produced, and is deprived, as the case may be, of ammonia, impurities, or heat. The current of gas passes through the sheets of water, and, owing to the zigzag path that it is forced to take, throws the water in the form of fine spray or mist alternately towards the center and the periphery of the apparatus. It will be seen that in each washer the gas is washed many times, and that a most intimate contact will be caused between the gas and the washing liquid, while the distribution of the liquid and the washing of the gas are achieved with a very small power consumption. The use of packing or filling materials, such as coke, earthenware, tiles, or wooden boards, which baffle the passage of the gas, is completely eliminated, thus avoiding stoppages and troublesome renewals due to such fillings getting choked up. These washers are made in sizes dealing with from 10,000 to 2,000,000 cu. ft. per hour in a single unit. With this modified washer, a plant originally designed to deal with the gas from 45 to 50 tons of coal per day was able to deal with that from 90 to 100 tons per day, so that the capital outlay of the gas washing part of the plant was reduced one-half. The dimensioning of the washers is not a very simple matter, being of necessity purely empirical, and has been arrived at entirely by stepwsic trial.

Steel is used as structural material for the parts of the ammonia absorbing apparatus and has proved much more satisfactory

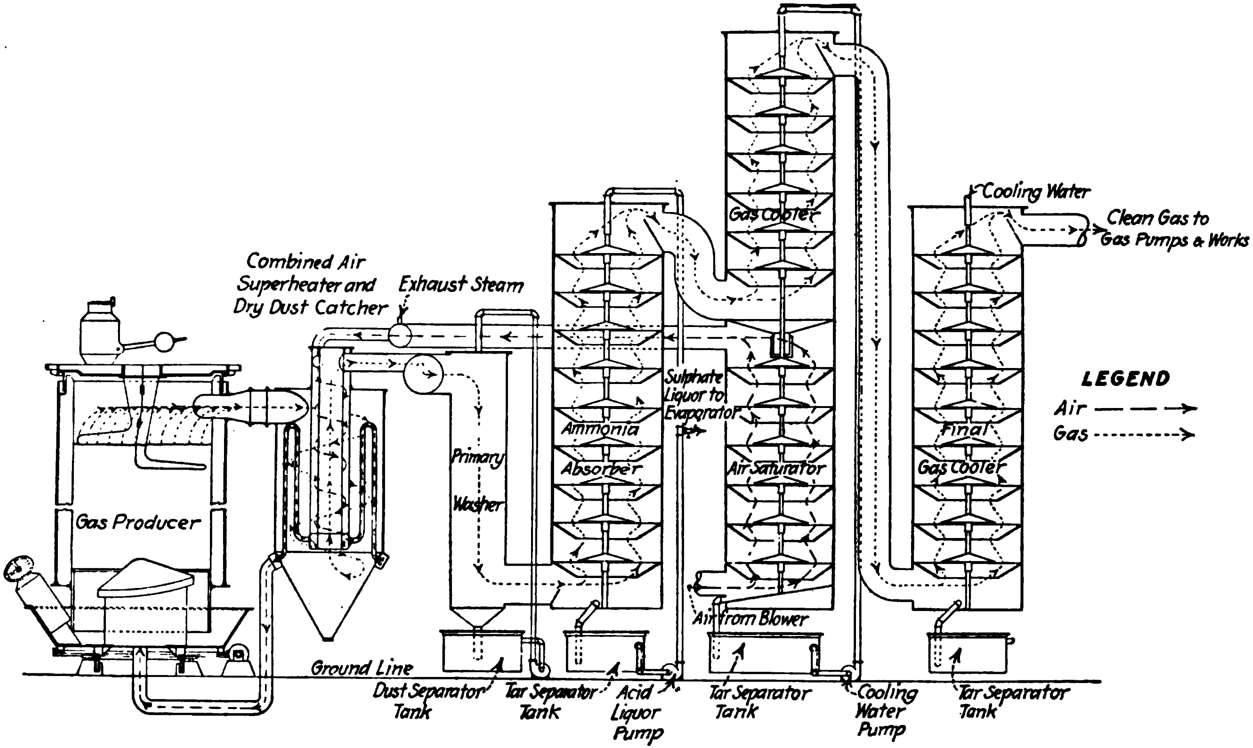

FIG. 81.—Lymn system of producer gas plant with by-product recovery.

than lead, which was used in older plants. A Lymn plant constructed with no lead whatever was operated in Germany for the 4 years prior to 1915,* without any corrosion being discovered.

New Type of Superheater.—Another improvement, made and patented by Lymn and Riley, was a more compact type of superheater (*C*), shown in Fig. 81. This, in one form, consists of six vertical mild-steel shells concentrically arranged in such a way as to form five annular spaces and one cylindrical space. The three narrow spaces serve as passages for the air and steam blast on its way to the producers, and the wider spaces serves as passages for the hot gas leaving the producers on its way to the washing plant. The gas enters the apparatus tangentially at the top, and is given a cyclonic motion, thus facilitating the removal of the dust in its dry state. The coarser dust settles in the hopper bottom of the superheater, while only the fine dust is carried over to the washing plant. This greatly reduces the troublesome labor of removing the dust from the sumps in its wet state.

The gas is conducted downwards in the outer space, whence it enters the next annular gas passage nearer to the center, in which it is conducted upwards towards the top, where it again changes its direction and passes to the innermost gas passage, which, at the same time, serves as the outlet pipe for the gases. The air and steam blast passes through the narrow annular spaces in counter-current direction to that of the gas, and, as both the cylinders forming the air conduit are surrounded by the hot gas, an immediate superheating of the air and steam mixture takes place, while, at the same time, no heat losses to the outside can occur. It will be obvious from this construction that no parts of the apparatus are subject to extreme temperature differences, thus eliminating expansion troubles. Owing to the air conduits being placed concentrically one inside the other, the loss of heat to the outside is reduced to a minimum. Their design renders possible regular cleaning without stoppages and consequently a constant efficiency is maintained. Another type of superheater is built in the same general shape, but is constructed of tubes in place of concentric cylinders (Fig. 78). The tubular form can be built at lower cost in the United States.

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* A. H. Lymn (*loc. cit.*, p. 330).

After the previous mentioned failure of the revolving shell producer, Lymn carried on in England further trials of mechanical agitation and ash removal. Riley at the same time was experimenting along similar lines on American caking and coking coals. These experiments resulted in a design of producer based on the principle which has been so largely utilized. for ordinary hot-gas producers in Europe. The rotary grate and the mechanical ash removal have been further constructionally improved, and very widely introduced, both by Kerpely of Vienna and by Lymn's German licensees. On the basis of the last-named firm's designs as adopted for hot-gas producers, the system has been applied to ammonia recovery, material modifications being of course necessary. These modifications are to provide a vastly increased volume of air and steam, a deeper fuel bed, superheating of the blast of air and steam, increased pressure of the air blast and consequently deeper water lute, etc.

A number of plants in Germany and elsewhere are using this Lymn-Riley and Rambush patented producer. In this producer the whole of the lower layers of the fuel and the whole of the ash zone are kept in a state of very gradual but constant movement, and it will be seen (in Fig. 81) that the producer grate, or air distributor, has the shape of two vertical half cylinders laterally displaced along their dividing surface. The top of each half cylinder has the shape of a half propeller or spiral, so that, during each succeeding half revolution, a vertical propeller-like movement is imparted to the ash and fuel, in addition to the eccentric movement caused by the two laterally-displaced half cylinders. As the air blast inlet is always receding from the ashes or fuel placed above it, it is always open and free. The small ash ploughs (*B*), of which a few are fixed at the bottom edge of the producer shell, remove the ashes constantly from several different points, directly beneath the producer proper, outwardly into the revolving ash trough, from which the ash shovel discharges them. The two-stage ash removal may appear more complicated than a single-stage mechanism. In practice, however, it is a simplification, as the work is divided between the ploughs and the shovels, the ash ploughs moving the ashes from under the producer proper into the trough, leaving to the ash shovel the simple duty of finally discharging them. It has been found that with this method the fire in the producer burns much more evenly, and that fuels containing much ash can be handled continuously and successfully, which with the one-stage discharge have caused repeated breakdowns. Owing to the excess of steam used in the by-product producer, the temperature of the fire is kept comparatively low and the formation of clinkers is prevented.

In addition to the mechanical bottom, a mechanical top is also used to handle caking coals. This consists of an agitating device which breaks up any mats in the top zones of the producer, eliminates blow holes and materially decreases the amount of labor necessary for poking.

General Description of Plant.—In Fig. 81, which shows a Lymn plant diagrammatically, dotted lines are used to show the current of the gas, whereas dot and dash lines are used to show the direction of the air. The air is delivered by a set of high-pressure blowers to the bottom of the air saturator, *A*, which occupies the lower half of the cylinder forming the combined air saturator and gas cooler. The circulating water is pumped from the sump, *S*, to the top of this tower and is showered down through the warm gas from which it absorbs heat. It then flows through a small opening in the partition which separates the upper and lower chambers and is showered down through the incoming air, warming it and saturating it with moisture. Practically no loss can occur in the transference of heat from the gas passing through the gas cooler to the air passing through the saturator on its way to the gas producers. In older types of plant the water used for saturating the air is passed through long lengths of piping and tanks, thus losing heat before entering the air-saturating apparatus. This combination avoids the duplication of settling tanks, pumps, and pipe systems, thus saving considerable space and capital outlay. The air then passes to the superheater. Before reaching the latter, it is further saturated by the addition of exhaust steam. The superheater is another form of heat exchanger for preheating the incoming air with the heat from the gas leaving the producer. The air is then piped to the grate and passes upward through the fuel bed. The hot gases leave the producer at the top and pass through the superheater in the opposite direction from the incoming mixture of air and steam. The greater part of the sensible heat is abstracted from the gases and they pass into the gas main which collects the gas from the other producers. The gas then enters the vertical dust washer, *G*, in which the remaining dust, not already separated out in the superheater, is removed in a wet state by washing with water. Since ammonia gas is readily soluble in cold water, the temperature of the water in this washer is kept sufficiently high to prevent such absorption to any appreciable extent; moreover the water becomes saturated. The first dust washer, *G*, is often constructed in the ordinary form without baffles, the water issuing from spray pipe at the top and showering down through the full length of the vertical cylinder (Fig. 81). The simpler type of washer is preferable at this point for collecting the tar. From the dust washer the gas enters the static ammonia absorber, *K*, in which it is brought into intimate contact with an atomized solution of sulphate of ammonia containing a slight excess of sulphuric acid, which abstracts the ammonia. Next, the gas passes into the vertical static gas cooler, *L*, mentioned above, and thence into the final gas cooler, *M*, in which it is cooled and cleaned by means of cold water. It is then suitable for any ordinary industrial heating operation or for boiler firing.

The temperature gradients in the air and gas are approximately as follows:*

	Entering, degrees Centigrade	Leaving, degrees Centgrrade
Air heating:		
No. 3 Washer (air saturator)	30	70
Air main, steam added	70	90
Superheater	90	210
Producer	210	
Gas cooling:		
Superheater	500	360
No. 1 Washer	360	90
No. 2 Washer (ammonia absorber)	90	80
No. 3 Washer (gas cooler)	80	65
No. 4 Washer (gas cooler)	65	45

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* From a diagram in "Notes on Operating a By-product Producer-gas Plant for Power and Heating," by W. H. Patchell, read before The Institute of Electrical Engineers (England), March 11 and 18, 1920.

If the gas is to be used in internal combustion engines, further cleaning is necessary. First, it is passed through one or two centrifugal cleaners, where it is almost entirely freed from tar, and thence, after traversing a special water spray separator, it passes through dry scrubbers filled with sawdust or wood shavings, in which the last traces of tar are removed.

The circulating vessels and tar-separating tanks, designated *S*, receive the water or liquor from the washers, whence it is continuously repumped to the washers. The concentrated sulphate liquor produced in the ammonia absorber, *K*, is transferred to a vacuum-evaporating plant, in which it is further concentrated by boiling and the salt crystallized out. The salt is finally dried in centrifugal hydro-extractors, from which it is conveyed to the sulphate store.

Steam Requirements.—A highly saturated air blast is essential to the recovery of ammonium sulphate, as it keeps down the temperature of the producer and thus prevents the destruction of the ammonia formed by the combination of the nascent hydrogen (derived from the steam) with the nitrogen in the fuel.

The Lymn system requires, in the producer blast, about 2.5 lb. of steam or water vapor per pound of normal coal gasified. The gas cooling and air saturating cycle of operations supplies about 1.0 lb., leaving 1.5 lb. to be supplied from external sources.

When the gas is used as fuel in a steam power plant, the feed water for the boilers may be heated to 170°F. (77°C.) in the tops of the producers. This will release exhaust steam from the power station auxiliaries from this duty and will render it available for saturating the air blast. Some additional steam will be required which may be bled from the main turbines or, preferably, from a non-condensing turbine exhausting at 1 lb., or less, above the atmosphere.

FUELS AND PRODUCTS

Bituminous Coal.—When gasifying a ton of eastern bituminous coal, the Lymn-Riley producer will generate gas and tar approximately as follows:

130,000 cu. ft. gas of 140 B.t.u. per cubic foot, net,
or
140,000 cu. ft. gas of 130 B.t.u. per cubic foot, net,
and
120 lb. tar of 18,000 B.t.u. per pound.

In England it has been found that, freed from water, this tar makes a most desirable covering agent and preservative for buildings, ironwork, etc., or it can be distilled into light oils and pitch, which command profitable prices. It is also used as a fuel for boiler-firing by means of a special burner.

Table XXXIV gives a comparison of the composition of the gas from by-product producer plants with that from ordinary gas producers. These two types of producer gas may be designated, respectively, as Mond gas and Siemens gas, after the inventors who did most of the pioneer work in the commercial development of each.

Mond gas differs from Siemens gas chiefly in that the carbon monoxide and hydrogen content are, broadly speaking, reversed, while the carbonic dioxide is very considerably increased, as will be seen from the representative analyses, obtained from the gasification of cheap bituminous coal.

TABLE XXXIV

	Mond gas with ammonia recovery	Ordinary producer gas	
Carbon monoxide (CO)	11.0	26.5	
Hydrogen (H_2)	27.5	8.5	Volume per cent. gases saturated at 15°C.
Marsh gas (CH_4)	3.0	3.5	
Carbonic acid (CO_2)	16.5	5.0	
Nitrogen and moisture (N_2 and H_2O)	42.0	56.5	
Total volume	100.0	100.0	
Total combustibles	41.5	38.5	
Calorific value (gas dry @ 15°C.):			
B.t.u. per cubic foot, gross	156.0	149.0	
B.t.u. per cubic foot, net	140.0	142.0	

The difference in the composition of the gases is due to the fact that, in the Mond system, the producer is worked with an air blast containing a large proportion of steam.

Chemistry of the Process.—E. Haanel[*] has presented a chemical consideration of the manufacture of Mond gas, with the recovery of sulphate of ammonia.

[*] Condensed from *Mines Branch Publication* No. **229**, pp. 82–92; Ottawa, Canada, **1914**.

The chemical reactions which take place in an updraft producer of the Mond type, in which the air blast is highly saturated with steam, are dependent on the following factors:

1. Temperature of the fuel bed.
2. Depth of fuel bed.
3. Rate of flow of gas through the fuel.

In considering the influence which any or all of these factors have on the formation of the final gas as regards its chemical composition and hence its heating value, it is necessary to consider separately the effect of the oxygen of the air on incandescent carbon, and that of the steam entering with the former.

Under ordinary circumstances, *i.e.*, when a shallow depth of fuel is completely burned, the solid carbon of the fuel burns directly to carbon monoxide with the evolution of heat. The reaction may be expressed thus—the quantity of carbon burned being 24 kg.

$$(a)\ 2C + O_2 = 2CO + 2 \times 29{,}000 \text{ cal.}$$

The carbon monoxide thus resulting is, however, almost instantaneously burned to carbon dioxide with a further evolution of heat. The equation expressing this reaction may be written thus:

$$(b)\ 2CO + O_2 = 2CO_2 + 2 \times 68{,}000 \text{ cal.}$$

As regards the final result, *viz.*, the formation of CO_2 and the generation of heat, it makes no difference whether the solid carbon is first burned to carbon monoxide, which is then burned to carbon dioxide, or whether the carbon is at once burned to carbon dioxide—the evolution of heat in both cases would be the same. These then represent the reactions which take place between the oxygen of the air and the carbon of the fuel when a shallow layer of fuel is burned completely, as on grate bars.

In the case of a gas producer, however, when incomplete combustion is aimed at, the carbon dioxide resulting from reaction (*b*) is again reduced to carbon monoxide in its passage upwards through the bed of fuel, and, as was stated before, this is dependent on the temperature and rate of flow of the gas through the fuel bed. The rate of flow of gas through the bed of fuel, or the time occupied by a molecule of the gas in traversing the entire depth of the fuel, determines the time of contact between the gas, or molecule of gas, and the incandescent carbon.

High temperatures favor the formation of carbon monoxide, while low temperatures favor the formation of carbon dioxide. Thus it will be seen that the quantity, or percentage by volume, of either carbon monoxide or carbon dioxide present in a producer gas, is dependent on the temperatures prevailing at different heights in the fuel; and that while, with a rise of temperature, carbon dioxide will be reduced to carbon monoxide, the carbon monoxide is as readily oxidized to carbon dioxide with a fall in temperature. In the first case, the reaction takes place with an absorption of heat, while in the second case the reaction is accompanied by an evolution of heat.

Thus the reaction between carbon and carbon dioxide is reversible and may be expressed as follows:

$$(c)\ CO_2 + C \rightleftarrows 2CO.$$

The arrow replacing the signs of equality in the above equation indicates that the reaction may proceed from right to left or from left to right. The concentrations of the reacting substances, together with the temperatures, govern the direction in which the reaction will proceed, and for every temperature there is a certain constant relation between the concentrations of CO and CO_2 in equilibrium with carbon.

According to O. Boudouard, the following mixtures of carbon monoxide and dioxide are in equilibrium with solid carbon under atmospheric pressure, at the temperatures given:

Temperature Degrees Centigrade	Percentages of	
	CO	CO_2
650	39	61
800	93	7
925	96	4

It will be seen that the reversible reaction (*c*) tends to increase the percentage of carbon dioxide in the resulting gas when the temperature of the zone of reaction in the producer is lowered.

The percentages of carbon monoxide and dioxide which are in equilibrium with solid carbon at various temperatures, have been more recently investigated by J. K. Clement, L. H. Adams, and C. N. Haskins.* The percentages of carbon monoxide in equilibrium with carbon, determined for temperatures ranging from

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* "Essential Factors in the Formation of Producer Gas," by J. K. Clement, L. H. Adams, and C. N. Haskins, Dept. of the Interior, Bureau of Mines, Washington.

500 to 1,600°C., do not agree with those determined by Boudouard, whose figures will, however, serve as a qualitative illustration.

It is also necessary to consider the reactions which take place between steam and incandescent carbon. At comparatively low temperatures (about 500 to 600°C.) steam reacts with carbon, in accordance with the equation,

$$(d)\ 2H_2O + C = 2H_2 + CO_2 - 19{,}000 \text{ cal.},$$

while at temperatures of 1,000°C. and upwards the main reaction involves the production of carbon monoxide and hydrogen, in accordance with the equation,

$$(e)\ H_2O + C = H_2 + CO - 29{,}000 \text{ cal.}$$

This reaction predominates in the manufacture of water-gas, which consists in blasting a producer with air and with steam alternately. The air blast is continued until the fuel reaches a temperature of incandescence; then the steam blast is admitted and continued until the temperature of the fuel bed falls below 1,000°C. During the air blasting both CO and CO_2 are formed by reactions (*a*) and (*b*).

According to Bone and Wheeler,* in steam blasting at temperatures between 600 and 1,000°C. the products correspond to a simultaneous occurrence of reactions (*d*) and (*e*), the second reaction gradually asserting itself as the temperature rises, until at 1,000°C. it entirely supersedes the first. Both reactions are endothermic, *i.e.*, absorb heat.

Bone and Wheeler suggest that the larger quantities of steam which are necessarily used in the Mond process, where the chief aim is the recovery of ammonia, may reduce the temperature in the producer sufficiently to allow a considerable occurrence of reaction (*d*) and that this would probably account for the relatively high percentage of carbon dioxide in Mond gas.

The products formed by the action of steam and carbon, according to equations (*d*) and (*e*), may undergo a readjustment in accordance with the equation,

$$(f)\ H_2O + CO \rightleftarrows H_2 + CO_2.$$

This reaction is reversible. At all temperatures above 500°C., or thereabouts, steam reacts with carbon monoxide and hydrogen with carbon dioxide. The direction in which the action proceeds

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* *Journal of the Iron and Steel Institute*, **1907**, No. 1, 129.

depends on the temperature and the relative concentrations of the reacting substances, so that, for every temperature above 500°C., there is a condition of equilibrium for which the product of the concentrations on one side divided by the product of the concentrations on the other side of the equation is a constant.

Thus: $$\frac{H_2O \times CO}{H_2 \times CO_2} = K = \text{a constant.}$$

This constant has been determined by Hahn* for temperatures between 786 and 1,405°C., as follows:

TEMPERATURE	K
786°	0.81
886°	1.19
986°	1.54
1,086°	1.95
1,205°	2.10
1,405°	2.49

A consideration of these equilibrium constants permits one to predict the direction in which the reaction will take place.

For example, in the case of a mixture which is in equilibrium at a comparatively low temperature, about 800°C., the reaction will take place in the direction

$$CO_2 + H_2 = CO + H_2O$$

As the temperature is raised, and it will proceed in the direction $CO + H_2O = CO_2 + H_2$ when the temperature is lowered. Addition of steam tends to lower the temperature; hence it will cause a change in the latter direction. When the reaction proceeds in the direction $CO_2 + H_2 = CO + H_2O$, there is an absorption of heat, while a change in the opposite direction involves a corresponding evolution of heat.

The introduction of steam into the reaction zone of a producer not only increases the thermal efficiency of the system but also reduces to a minimum clinker troubles which often arise when high temperatures prevail.

In the case under consideration, however, *viz.*, the gasification of a solid fuel with a view to recovering the maximum amount of ammonia, steam in excessive quantities is introduced for the purpose of carrying out the process, regardless of the thermal efficiency of the system.

As a result of the introduction of an excess of steam, the gas

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* *Zeitschrift f ür Physikalische Chemie*, 1903, **43**, 705; **44**, 513.

produced is inferior in heating value to that obtained when the Mond process is operated for power gas alone, hence its thermal efficiency as a power gas producer is sacrificed, to a certain extent, to the most efficient recovery of ammonia.

Several theories have been advanced regarding the manner in which ammonia gas is formed in the producer. A theory advanced by J. A. Weil, chief chemist to the Power Gas Corporation, seems to fully explain all the phenomena observed.

According to this theory, the ammonia is formed in two stages:

1. By low-temperature distillation of the fuel; in this stage a considerable amount of nitrogen is lost.
2. By the action of nascent hydrogen upon nascent nitrogen formed by the reaction of steam upon incandescent, nitrogenous, carbonaceous material.

This view is supported by temperature considerations; with a low concentration of hydrogen, less ammonia would be formed, and *vice versa.* As the temperature is reduced, the reversible reaction (*f*) will proceed in the direction $CO + H_2O = CO_2 + H_2$ with evolution of heat. The hydrogen concentration will be increased, and this is a condition for high ammonia yield.

The ammonia gas thus formed is passed through the absorber and comes into intimate contact with sulphuric acid, with which it reacts according to the equation,

$$2NH_3 + H_2SO_4 = (NH_4)_2SO_4.$$

The ammonium sulphate resulting is in solution with weak sulphuric acid—about 2 per cent. strength—and is recovered in crystalline form by evaporation.

Application of Mond Gas to Industrial Furnaces.—Applied to suitably designed furnaces, Mond gas is an ideal fuel. As compared with direct solid fuel firing, it ensures a higher temperature under absolute and easy control, reduced labor, elimination of the smoke nuisance, increased output of material, reduced stand-by losses, and a saving of from 30 to 50 per cent. in the consumption of fuel. The flame temperature of the gas is approximately as follows:

TABLE XXXV

Without pre-heating air or gas	950°–1,150°C.
Continuous air recuperation	1,150°–1,300°C.
Reversing air regeneration	1,300°–1,400°C.
Continuous gas and air recuperation	1,200°–1,400°C.
Reversing air and gas regeneration	1,400°–1,800°C.

In establishments requiring both power and heat, the advantages of a central by-product producer plant to supply both needs are very marked, the gas being delivered at about 30°C., containing only 4 per cent. of water vapor by volume and a small proportion of condensable tarry vapors.

Cool Mond gas has been applied to steel furnaces to a considerable extent. In firing the Siemens type of open-hearth furnaces, it has given results, in regard to output of material, fully equal to those obtained with hot raw producer gas.

Ammonium Sulphate.—The yield of sulphate that it is possible to obtain is dependent primarily upon the nitrogen content of the fuel. In many representative grades of bituminous coal mined on both sides of the Atlantic, this averages about 1.4 per cent., or 28 lb. of nitrogen per ton. With a theoretical recovery of 100 per cent., this would yield 132 lb. of $(NH_4)_2SO_4$. In both the Mond and Lymn systems it is common practice to recover from 60 to 70 per cent. of the nitrogen content, or, say, 80 to 90 lb. of sulphate per ton of bituminous coal.

The usual requirements for the manufacture of one ton of ammonium sulphate from ammonia is 0.96 ton of sulphuric acid of 60°Bé. gravity. The present works price for this acid (Oct., 1921) is between $11.00 and $12.00 per ton. Allowing for freight charges, we may assume a price of $12.50 to the consumer, or $12.00 per ton of sulphate produced.

The price of ammonium sulphate in this country may be considered to range from the pre-war value of about $70.00 per ton down to the present value of about $44.00 (Oct., 1921). After deducting the cost of the acid, the corresponding net prices are $58.00 and $32.00, respectively, or 2.9 and 1.6 cents per lb. When recovering 80 lbs. of sulphate per ton of coal gasified, the returns from its sale are $2.31 and $1.52 at the prices mentioned. The cost of recovery must, of course, be charged against this credit.

It is further evident that coals, or other fuels, of higher nitrogen contents give a decidedly greater return at no additional cost other than the cost of the acid. The economics of this process are further discussed at the end of this Chapter.

Tar.—The Crude tar is generally burned for fuel purposes and should have a value comparable with that of heavy Mexican oils. The yield per ton is approximately 15 gal. or 120 lbs. In England it is sometimes distilled, yielding light oil and pitch.

Bulletin **22** of the U. S. Bureau of Mines contains tables of the analyses of many American coals. Lymn has summarized the average nitrogen content of the samples for which this had been determined, in terms of percentage of theoretically dry fuel. The author has regrouped the statistics for the various States in Tables XXXVI and XXXVII, and has added the nitrogen content, based on the coal "as received," for the Eastern States and for the samples of lignite from North Dakota and Texas (Table XXXVIII). The latter figures should be of more practical interest. The average nitrogen content of the bituminous coals in the Appalachian States ranges from 1.22 in

TABLE XXXVI.—NITROGEN CONTENTS OF EASTERN COALS

State	Rank of coal	Number of samples analyzed for N	Nitrogen content, per cent. Dry basis, average	Nitrogen content, per cent. Coal as received Average	Nitrogen content, per cent. Coal as received Minimum	Nitrogen content, per cent. Coal as received Maximum
Rhode Island						
	Graph. anthracite	10	0.19	0.16	0.08	0.27
Pennsylvania	....	106	1.28			
	Anthracite	12	....	0.80	0.63	1.10
	Semibituminous	74	....	1.25	0.97	1.50
	Bituminous	18	....	1.40	1.05	1.57
Maryland						
	Semibituminous	15	1.71	1.66	1.29	1.82
West Virginia	....	265	1.37			
	Semibituminous	223	1.58	1.32	0.94	1.68
	Bituminous	38	....	1.40	1.12	1.58
Virginia	....	27	1.29			
	Semibituminous	8	....	1.13	1.02	1.21
	Bituminous	17	....	1.40	1.08	1.59
Ohio						
	Bituminous	16	1.30	1.22	1.06	1.42
Kentucky						
	Bituminous	22	1.42	1.35	1.06	1.83
Tennessee						
	Bituminous	15	1.46	1.38	0.98	1.75
Alabama						
	Bituminous	39	1.42	1.37	1.10	1.79
Georgia						
	Semibituminous	1	1.13	1.09		

TABLE XXXVII.—NITROGEN CONTENTS OF WESTERN COALS

Province	State	Rank of coal	No. of samples	Average nitrogen content, dry basis
Interior		Bituminous		
	Michigan		2	1.38
	Indiana		23	1.27
	Illinois		67	1.28
	Iowa		15	1.16
	Missouri		40	1.11
	Arkansas		18	1.41
	Kansas		30	1.24
	Oklahoma		20	1.63
Gulf		Lignite		
	Texas		5	1.16
Northern Great Plains		Lignite		
	North Dakota		6	1.13
Rocky Mountain		Bituminous and subbituminous		
	Montana		81	1.03
	Wyoming		192	1.30
	Colorado		176	1.36
	New Mexico		27	1.29
	Utah		32	1.11
	Arizona		1	1.25
Pacific Coast		Bituminous and subbituminous		
	Washington		169	1.58
	Oregon		1	1.42
	California		4	0.97
	Alaska	All ranks	45	1.14
Total for United States			1,467	1.325

Ohio to 1.4 in Pennsylvania, West Virginia and Virginia. Several regions in the Central and Western States contain bituminous coals with high nitrogen contents.

In the semibituminous coals it ranges from 1.13 in Virginia to 1.66 in Maryland. The average nitrogen content for semibituminous coals is lower than for the bituminous, but in some districts the analyses show a consistently high value, notably in Maryland and in parts of West Virginia.

TABLE XXXVIII.—ANALYSES OF AMERICAN LIGNITES

Location of mine	Laboratory No.	Basis	Moisture	Vol.	F. C.	Ash	N	B.t.u.
			Per cent.					
McLean Co., North Dakota								
Wilton	.....	Mois.	36.0	32.0	24.4	7.7	1.21	7,069
	2,243	Dry	....	49.8	38.0	12.1	1.89	11,038
Stark Co.								
Lehigh	.....	M	35.4	29.6	25.7	9.3	0.54	6,923
	1,279	D	....	45.8	39.7	14.5	0.84	10,714
Lehigh	2,289	M	32.6	29.2	26.7	11.4	0.49	6,970
	.....	D	....	43.3	39.7	17.0	0.73	10,346
Williams Co.								
Williston	.....	M	36.8	28.2	30.0	5.1	0.69	7,204
	1,416	D	....	44.5	51.6	8.0	1.09	11,394
Williston	2,365	M	36.1	29.3	29.5	5.0	0.73	7,326
	.....	D	....	45.8	46.3	7.9	1.14	11,473
Williston	4,276	M	39.0	25.5	30.2	5.4	0.68	6,739
		D	....	41.8	49.4	8.8	1.11	11,034
Houston Co., Texas								
Crockett	.....	M	34.7	32.2	21.9	11.2	0.72	7,056
	1,456	D	....	49.4	33.5	17.1	1.10	10,805
Milam Co.								
Olsen	.....	M	31.0	27.7	33.4	7.9	0.90	7,870
	2,734	D	....	40.1	48.4	11.4	1.31	11,416
Wood Co.								
Hoit	.....	M	28.9	36.0	27.3	7.9	0.80	7,996
	1,241	D	....	50.5	38.3	11.1	1.12	11,239
Hoit	1,597	M	33.7	29.2	29.8	7.3	0.79	7,348
	.....	D	....	44.1	44.9	11.0	1.19	11,084
Hoit	2,717	M	33.8	27.5	31.3	7.3	0.71	7,497
		D	....	41.6	47.4	11.0	1.07	11,333

These coals are less tarry than high-volatile coals of bituminous rank and should, therefore, be more readily handled in a producer. Artificial fuels of similar composition may be prepared by distillation of bituminous coal at low temperature and these can be burned in gas producers with the same facility as anthracite.

Lignite.—In lignites the nitrogen content of the raw fuel, on account of the high-moisture content, is naturally lower than in coal. The samples of lignite in Table XXXVIII, from Texas and North Dakota, represent some of the most difficult fuels to burn under boilers owing to this high-moisture content. Table XXXIX indicates results attained some years ago in burning European lignites in Mond gas plants. The tar yield is greater than with ordinary bituminous coal, varying from 10 to 15 per cent. The fuel is fired without preliminary drying, thus avoiding

TABLE XXXIX.—USE OF LIGNITE IN MOND PLANTS IN EUROPE

Source of fuel		Sodingen, Westphalia	Savoie, France	Ribollo, Italy
Analysis of Fuel		(OVER LONG PERIOD)	(TEST)	(TEST)
	Moisture	32 to 36	40.5	8.5
Dried at 100°C.	Ash	22 to 27	17.7	16.2
	Volatile matter	....	50.1	
	Nitrogen	0.86	1.83	1.9
	Total carbon	....	49.9	59.3
	Fixed carbon	....	33.9	
	B.t.u. 1 lb.	....	8,761.0	
	B.t.u. as fired	5,220 5,580		
Average analysis of gas:				
	CO_2	15.0	20.8	16.3
	O_2	0.2	0.2	0.2
	CO	13.0	10.6	11.5
	H_2	24.8	25.6	26.3
	CH_4	4.5	5.4	4.8
	N_2	42.5	37.4	40.9
		100.0	100.0	100.0
Combustible gases		42.3	41.6	42.6
Calorific value, gross B.t.u.		178.0	182.0	174.0
Calorific value, net 1 cu. ft.		161.0	163.0	158.0
Yields per ton of dry fuel:				
	Gas, cubic feet @ 15°C.	70,500.0	78,300.0	71,700.0
	Ammonium sulphate, pounds	61.3	92.5	130.0
	Tar, pounds	333.0	....	315.0
	Tar, per cent.	14.8	....	14.06
Screen analysis of fuel:				
	Largest piece	....	5 × 3 × 1½ in.	1 × 1 in.
	Over ½-in. mesh	....	100 per cent.	50 per cent.
	Between ½ and ⅛-in. mesh	....	....	25 per cent.
	Below ⅛-in. mesh	....	....	25 per cent.

loss by disintegration, and may contain as much as 50 to 60 per cent. of moisture without detriment to the quantity or quality of the gas, ammonia or tar produced. In burning very moist fuels the gas is cooled before leaving the producer by the vaporization of the moisture. It is, therefore, in some cases, necessary to use gas-fired superheaters for the air supply.

Peat.—The Mond gas process was successfully applied to the gasification of peat between 1904 and 1907. The drying of peat is a most difficult matter and in view of this fact it is interesting to note that today it is possible to produce regularly power gas and by-products from peat containing up to 50 or 60 per cent. water. This peat can be obtained by relatively short periods of drying in the atmosphere in practically all countries. The best results, however, are obtained where the moisture-content does not exceed 35 per cent.*

A plant dealing with 100 tons of peat per day, and producing ammonium sulphate and power gas, has been in operation at Orentano,† in northern Italy, since about 1911. The peat is dried to an average moisture content of 33.5 per cent. and has an average nitrogen content of 1.04 per cent. The gas is used to operate two 350 hp. gas engines and the power is transmitted to Pontedera, 10 miles distant. The plant is located at the edge of a bog with an area of about 1,482 acres and an average depth of about 5 ft. It has to be drained by pumping. The drying of the peat is discussed in another place (page 378).

TABLE XL.—RESULTS WHEN USING PEAT IN MOND GAS PLANTS

Source of fuel	Germany	Italy	England
Moisture content, per cent.	40 to 60	15.0	57.5
Nitrogen content (dry basis)	1.0	1.58	2.3
Yields per ton of theoretically dry peat:			
Ammonium sulphate, pounds	70.0	115.0	215.0
Gas, cubic feet	85,000.0	60,000.0	90,000.0
Calorific value of gas, B.t.u. 1 cu. ft., gross	150.0	166.0	134.0

The yield of ammonium sulphate ranges from 70 to 220 lb. per ton of dry peat, according to the nitrogen content, which is often greater than with coal (see Table XLI). The tar is quite

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* HAANEL, *J. Am. Peat Soc.*, April, **1921.**

† "The Utilization of Peat," *Nature*, **97** 19 (March 2, 1916).

different from that produced from coal, and, upon distillation, yields paraffin wax, lubricating oils, creosote, Diesel fuel oil and pitch. Some of its constituents can be used for making powerful disinfectants. The aqueous distillate from the producer contains methyl alcohol, acetone, pyridine bases and crude acetic acid, all of which are recoverable. Peat ash contains potash and phosphoric acid and may be put back on the land, after excavating the peat, to fertilize the soil and render it suitable for cultivation.

TABLE XLI.—ANALYSES OF AMERICAN PEATS*

State	Number of samples analyzed for N	Nitrogen content, per cent Dry basis		
		Average	Minimum	Maximum
Maine	51	1.32	0.60	2.28
Connecticut	3	1.86	1.48	2.17
New York	5	2.25	1.48	2.63
North Carolina	1	1.68		
Florida	13	2.00	0.13	2.61†
Michigan	1	2.45		
Wisconsin	4	2.35	1.71	2.95

* Compiled from list of analyses in **16**, U. S. Bureau of Mines, *Bull.* **16**, 1911; "The Uses of Peat," by C. A. DAVIS.

† Other Florida peats are reported by private individuals to run as high as 3.5 to 4 per cent. N.

Plants in Operation.—Up to 1915 about 60 by-product producer plants had been built, having a total yearly capacity of approximately 2,000,000 tons of fuel. The greater number of these are located in Great Britain and the remainder are distributed among Germany, Italy, Spain, China, Japan and the United States.

The gas from them is being used not only for power production but also for all kinds of industrial heating operations, such as reheating furnaces, forging furnaces, annealing furnaces, steel furnaces, core stoves, crucible heating, galvanizing baths, gas works retort firing, spelter furnaces, glass works operations, evaporating brine, calcining operations, roasting operations, etc.

Few industrial processes lend themselves to introduction into a foreign country without alteration to meet local conditions and fuels. Some mistakes have been made in the past owing to too rigid adherence to European designs. The recognition of these facts has led to the installation of two plants in the United States, each of about 100 tons of coal gasifying capacity, which were designed by Messrs. Lymn and Riley and in which American fuels are being gasified on a large scale. The first of these was installed at Irwin, Pa., by the Westmoreland Coal Co., and the second one at Fairmont, W. Va., by the Monongahela Valley Traction Co. (Fig. 80). At both places they operate on highly caking coal.

In most of the foreign plants using producer gas for generating power, the gas engine has been used as prime-mover.

Fushun Colliery Plant of the South Manchuria Railway.*— A by-product producer plant for supplying producer gas to a steam-power station was installed at the Fushun Colliery of the South Manchuria Railway. This is owned by the Japanese Government and will ultimately have a capacity of 1,000 tons of coal per day. The first half of the plant was built on the Mond system and has been in operation since December, 1914. Figure 82 is a view of the producers with the coal bunkers located above them. They are of the Mond single shell type, 11.5 ft. inside diameter. Ten of these, placed in one row, gasify 240 tons of coal per day. The bunkers have a capacity for storing 450 tons.

The boiler equipment consists of eight Babcock and Wilcox boilers designed to burn Mond producer gas. Arrangements are also made so that four units may be coal fired, while one is also designed for tar firing. The original steam installation consisted of mixed-pressure turbines of 3,000 kw. total capacity and of European manufacture. This application of gas-producer plant, gas-fired steam boilers, and mixed-pressure turbines for supplying the necessary low-pressure steam to the producers, is probably the first of its kind ever tried; and 5 years, experience has proved the operation to be very economical.

The heavy demand for ammonium sulphate and the rapid progress in developing the mines necessitated the extension of the

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*Information from the International General Electric Company. Also from "The Fushun Colliery & Power Plants of the South Manchuria Railway," by S. Nakaya and J. R. Blakeslee, *Gen. Elec. Rev.*, September, 1917. And from "Lymn By-product Producer-gas Plant and the Utilization of Low-grade Fuels," *Iron & Coal Trades Review*, March 8, 1918.

plant. Extensions to the producer plant have been built on the Lymn system, the first consisting of 14 producers with a total daily capacity of 260 tons. This supplies gas to an extension of the power station containing three 3,000-kw. Curtis turbines of General Electric manufacture. Two of these units operate condensing and one non-condensing, the exhaust steam being used in the producers.

There are at present two power stations. Plant No. 1 is a steam-power plant, coal being burned under the boilers. This station has a capacity of 4,500 kw. in high-pressure condensing turbines and is equipped with Babcock and Wilcox boilers, mechanical stokers, and superheaters.

FIG. 82.—Installation of Mond by-product gas producers at Fushun Colliery. Coal bins are located above the producers.

The by-product producers are installed at plant No. 2, which is connected in parallel with station No. 1 and runs continuously at full load, while the latter takes care of the peaks. The two stations operating together have an ultimate capacity of 16,500 kw. It is expected that a peak load of 9,000 kw. (65 per cent. load-factor) will be required for mining, railway, and lighting, while the surplus power will be sold to an electrochemical company manufacturing ammonium sulphate by the cyanamide process. The entire station load-factor is therefore expected to be 100 per cent.

The coal field covers an area of about 19 square miles and coal is mined from three pits, two shafts, one slope and one open cut. The main coal-bearing district consists of shale with a thick coal seam. The shale overlying the coal is very thick and partly bituminous, being about 2,000 ft. measured by out-crops. The seam varies in thickness from 78 to 280 ft.; and the coal obtained is bituminous caking of a very uniform quality and is especially suited for gas making and steam raising. The analysis of an average sample is as follows:

Moisture	7.00 per cent.
Volatile matter	40.00 per cent.
Fixed carbon	48.00 per cent.
Ash	4.00 per cent.
Sulphur	0.80 per cent.
Specific gravity	1.28 per cent.
B.t.u. per pound of coal	12,400

Fushun coal is rich in nitrogen, some portions of it having a content of 1.8 to 2.0 per cent. The average nitrogen content is about 1.5 per cent. The refuse coal, which is picked away with slate in the screening house, contains 1.0 to 1.2 per cent. of nitrogen and 30 per cent. of ash. This refuse is mixed with an equal quantity of marketable coal to give a fuel of 20 per cent. ash content for use in the producer plant. About 95 lb. of ammonium sulphate are recovered per ton of this mixture.

Economic Size of Plant.—No general rule can be made on this subject, as the economic size of plant is determinable only after a careful study of local conditions and is naturally governed by a large number of factors. It can generally be said, however, that as far as the producer or gasifying portion of the plant is concerned, this is not materially affected by size, the cost of plant and operation varying quite closely with the size. On the ammonia recovery end, the larger the plant the less the capital cost per unit of plant, and, naturally, the larger plants operate on a somewhat more economical basis.

The entire economics and size of these by-product gas plants revolve around the consideration of whether the specific proposition is considered from the standpoint that the gas is the main product and the ammonium sulphate the by-product, or the reverse.

The maximum size of plant is, of course, limited first by the available fuel supply; for example, in the case of a peat plant by the extent of bog in the vicinity or, in the case of a plant using a low grade of mine waste, by the output of this waste. Secondly, it is limited by the demand for the gas, in case the fuel is not of high enough nitrogen content to allow of all or a portion of the gas being considered of no value and allowed to go to waste.

One of the main factors, which determines minimum size, is the ratio of the nitrogen content of the coal or other fuel to the cost of fuel and the value of the gas as fuel. Generally, it may be stated that the higher nitrogen coals, or other fuels, at lower prices warrant smaller plants, and that plants of one or two producers show adequate returns. Small plants are also warranted where there is a constant demand for cool clean gas; and the higher the value of this class of gas to the user, the lower may be the ratio of the nitrogen content to the cost of the fuel, and the smaller the economic size of plant. One of the most successful Lymn plants in England is a two-producer plant working on a coal of about 1.3 per cent. nitrogen, supplying gas to a manufacturing company for use in a gas engine electric generator set and to industrial furnaces.

Another factor determining economic size of plant, is that pertaining to the use of these plants in connection with what might be called allied industries, such as for firing by-product coke ovens in order to conserve the richer coke-oven gas for general distribution or, in the case of oil refineries, for the firing of stills; or, in general, in plants for manufacturing other types of gases or for carbonizing fuels. In the case of coke oven plants, for example, the availability of breeze for producer fuel, and the fact that a portion of the ammonia recovery part of the plant can be combined with similar processes connected with the coke ovens, will effect a decided economy.

Another factor in determining the economic size of plants is the question of the quality of the coal used, irrespective of its nitrogen content. A plant gasifying a good grade of run of mine or ¾-in. lump coal, for example, would consist of four or five units, whereas a plant using a slack coal would require five to six units in order to do the same work.

As a matter of general interest, it may be mentioned that the Lymn and Mond interests have recently been consolidated, and that Mr. Lymn is once more the technical director of the Power Gas Corporation.

The author wishes to acknowledge the assistance of P. A. Staples, representative of the Power Gas Corporation in New York City, in the preparation of this section of the Chapter and the one on the gas-fired boilers near the end of the Chapter, on page 386.*

GASIFICATION OF LOW-GRADE FUELS

We shall now consider the possibilities of some types of gas producers, other than those designed especially for ammonia recovery, for furnishing cheap gas for power purposes. Producers have been developed for gasifying almost any kind of solid fuel and some English manufacturers claim that their producers will gasify colliery refuse containing 45 to 55 per cent. of ash. The better practice, however, is to wash the refuse before using it, which will reduce the ash content from an original value of more than 50 per cent. to about 25 per cent. in the final product.

The gas producer has limitations similar to those of the steam-boiler furnace, in that its maximum output is roughly proportional to the heat value of the coal used. Therefore, low-grade coals require a larger grate area for a given output.

R. H. Fernald† comments, in part, as follows on European practice:

One of the most serious difficulties encountered in the use of high-ash fuels is excessive clinkering. The interruptions from such clinkering and the failure of the plant to develop rated capacity for continued periods make the satisfactory use of such fuels questionable. The attempt to use these poorer grades of fuel is not new, but their commercial application on a scale large enough to make their use really worth while industrially, and on a scale large enough to be a real factor in economic fuel utilization, is a recent development.

The demand for a gas producer to handle all grades of fuel, especially those grades usually sent to the dump, has recently

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*L. A. Riley, 2nd, the former representative, retired from business in 1920, owing to ill health, and the agency was continued for a few months by his associate, Mr. Staples, until the business depression of 1921 made it necessary to close it.

†R. H. Fernald, "Notes on the Use of Low-grade Fuel in Europe," *U. S. Bureau of Mines Tech. Paper* **123**, 1915.

brought to the European market the revolving eccentric-grate producer. This producer appears in several forms, the superiority of each form being firmly established in the minds of its advocates.

Experience with European fuels has shown that, even with the eccentric revolving grate and the usual producer-shell construction, clinker troubles are not entirely eliminated when a low-grade fuel with low ash-fusing temperature is used. A further important feature—probably the most important single item—for overcoming clinkering and the tendency of the ash to fuse with the producer lining is water-jacketing the part of the producer shell surrounding the hot zone.

The cost of construction of these revolving-grate jacketed producers is necessarily high, and a direct comparison of their cost with the simpler stationary-grate jacketless type is of course detrimental to the former.

During the past 5 or 6 years many installations of these producers have been made in Germany and other continental countries for gasifying low-grade fuels that have heretofore been neglected. Indifference to the use of high-ash clinkering fuels has been equally marked in England, but within the past few years a notable change in attitude toward this problem is evident and several installations have been made for the express purpose of utilizing low-grade material.

An engineer of London, however, who seems vitally interested in the greater economy desired in the use of our fuel resources, believes that for the present the commercial solution is not in the use of low-grade fuels, but in the more efficient use of the better grades. With the eccentric revolving grate producer he believes it is quite possible to handle almost any fuel, but the commercial economy is so low with the poorer grades, as the capacity of the plant is so greatly reduced, that he believes it to be a serious financial loss to use anything but good fuel. He believes that powdered fuel is perhaps the most promising solution of our fuel problems.

Use of Colliery-refuse Heaps as Fuel.—A large plant in connection with a colliery and iron works equipped with eccentric-grate producers was reported by the producer representative to be using high-ash "batts." On visiting the plant, however, Fernald found that the producers had not been operating upon "batts" for some time, although the general manager was seriously interested in the use of waste material and in the economies that are essential today in a well operated plant.

The colliery-refuse heaps in that vicinity have been accumulating and standing unused for years. A few years ago he began using selected "batts" from these dumps; that is, the larger pieces of shale containing a good percentage of coal. He has put in a crusher at the dump and is crushing the larger material and mixing in the fine, so that the whole dump is being reduced. This material is not used directly in the producers, but is sent first to the washers, and the washed coal is used; 115 tons of the unwashed material give 60 tons of numbers 1, 2, and 3 nuts and 40 tons of slack. This material was reported as containing about 25 per cent. ash when used in the producers.

Samples taken at the time of the inspection of the plant and sent to the Washington office of the Bureau of Mines were analyzed. The calorific value averaged about 10,200 B.t.u. per pound.

Pulverizing has been widely advocated as the best method for burning low-grade fuels and it undoubtedly has a promising future in this field. It is hardly likely, however, that any one method will prevail for utilizing all kinds of low-grade fuels, as each method has its advantages as well as its limitations. A high-ash content makes it necessary to pulverize a large proportion of inert material and imposes limitations in the application of pulverized fuel to some industrial processes. A high-moisture content makes the preliminary drying of the fuel expensive. A low volatile content precludes its usefulness in many industrial furnaces. Coke breeze and anthracite slush are considerably more difficult to pulverize than bituminous coal.

The Horizontal Rotary Producer.—E. L. Broome* is of the opinion that the chief competitor of pulverized fuel will be cheap producer gas; that is, good producer gas made from cheap fuel, such as anthracite slush or washery waste, bone coal, bituminous screenings, "duff" from the Middle Western deposits, coke breeze, lignites, peat and waste wood.

Most present day producers, whether static or mechanically stirred, cannot, or at any rate do not, use much smaller fuel than that corresponding to No. 1 buckwheat, because the finer kinds pack and prevent the passage of air, or the bed must be too

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*General Reduction Gas & By-products Co., 49 Wall St., New York, N. Y.

shallow to permit efficient reduction of CO_2. Again, a high percentage of ash results in excessive clinkering, which is expensive to overcome even in the eccentric grate type, and in the best of them the gas is quite irregular, so that it is evident a producer must be found which can use fine grades of fuel, such as much of the present mine waste consists of. Such a producer must have a continuous feed, deliver gas of uniform thermal value, and must automatically agitate the fire and fuel bed, and automatically and continuously discharge clinker and ash.

The General Reduction, Gas and By-products Co. been engaged for several years past in the experimental development of such an apparatus. The gas producer illustrated in Fig. 83 is the crystallization of a series of experimental machines, and embodies ideas and inventions resulting from such experiments. Modifications of this machine have been used with considerable success on Illinois screenings, lignite slack, anthracite slush, coke breeze, peat, and sawdust.

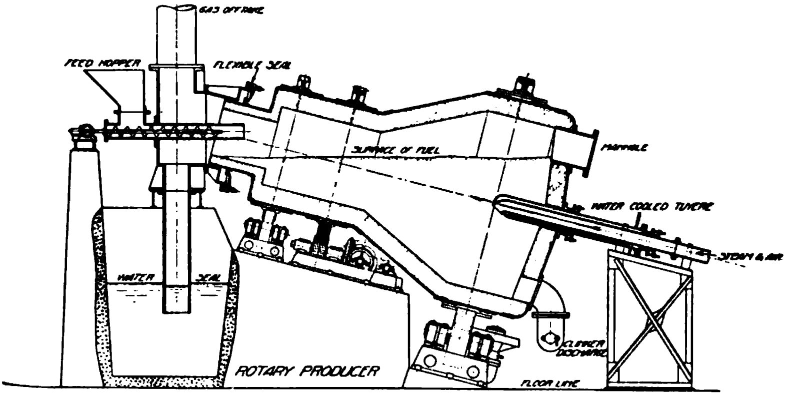

FIG. 83.—Horizontal rotary gas producer, developed by the General Reduction, Gas and By-products Company.

The apparatus consists, essentially, of a revolving horizontal drum, a modified cement kiln. Fuel is fed continuously and proceeds toward the fire, being deprived of moisture and volatile matter which is gasified at low temperature. Because of the constantly agitated fire bed, it is possible to maintain a comparatively deep bed which, unlike in other producers, is intensely hot throughout and in the condition usually considered desirable for the reduction of CO_2 to CO. Air and steam are introduced through the water-cooled tuyere which is bushed through a stuffing box in the center of the lower head, as shown.* The progress of the fuel across the hot zone is very slow, owing to the enlarged diameter, and during the time required to traverse the zone the fuel is changed to gas and ash, and the clinker is rolled up into balls and passes out with the ash.

These clinker balls are shown in Figs. 84 and 85. They probably form after the combustible matter has been entirely burned, as they contain not more than 3 per cent. of combustible, and this appears only on the surface where it has evidently been rubbed in while the balls were rolling in contact with partially burned fuel. A 12-in. rule is shown resting on a large ball.

Fig. 84.—Clinker balls discharged from a gas producer of the horizontal rotary type.

Anthracite slush, containing 20 per cent. moisture and 25 per cent. ash, has been gasified without any unsurmountable difficulties. A mixture of coke breeze and slush, containing 45 per cent of ash, has been burned with satisfactory efficiency. Several grades of Illinois coal, including screenings, gave promise of good results. Air-dried peat made excellent gas, but the available supply was so small that no conclusive results could be secured. It is apparent from the nature of the operation that a very high

*In a still more recent design (than that shown in Fig. 83), the tuyere is bent further downward, in order to introduce the air into the fuel at a lower level, and thereby increase the effective depth of the fuel bed and the length of time that the gases remain in contact with the fuel.

percentage of moisture does not interfere with gasification. In an earlier and less developed form of the apparatus, slack lignite from Wyoming made excellent gas with an efficiency of over 75 per cent. A similar machine has gasified sawdust at a thermal efficiency of over 80 per cent. Installations of such machines in connection with the enormous sawmills along the southern coast and at some inland points, with gas or power transmitted to nearby cities or manufacturers, offer a local solution of the fuel conservation question, even if no attempt is made to recover by-products, such as methyl alcohol, from the low-temperature gases. By providing suitable feeding mechanism, it should be possible to gasify other kinds of waste wood which could be fed in larger sizes. So far, these producers have been used for generating hot raw producer gas and it has been planned to install them directly under, or alongside of, a boiler.

FIG. 85.—Clinker balls discharged from a gas producer of the horizontal rotary type.

It would also seem possible that this type of machine would have considerable possibilities as a by-product producer in connection with the process for recovering ammonium sulphate. The designers consider that it should give more constant results, and have a relatively greater capacity, than producers of the static type. Also, there may be many kinds of fuel which it can handle more readily.

The depth at which the tuyere is submerged in the fuel is less than in by-product producers of the static type. In some cases this distance has been about 1 ft., but the average temperature of the charge is higher and, moreover, it is uniform throughout this depth. As an interesting comparison, a small static producer for motor vehicles has been described by D. J. Smith,* in which the depth of the fire is only 6 in.

In by-product producers of the static type, the incoming raw fuel is subjected to distillation by the passage of hot gases rising from the fire below. The tar distilled from bituminous coals and lignites during this stage of the process, however, is not particularly valuable since it has been fractionated by further distillation only into light oils and pitch. In the Bussey process (page 434) bituminous and cannel coals have been distilled at low temperature in a similar way by the partial combustion of the residual semi-coke at the bottom of a deep column of raw fuel. The tar resulting from this more gradual distillation has been fractionated by further distillation into a series of valuable oils, such as are produced from the low-temperature distillation of bituminous coal in closed retorts (Chap. VII).

As mentioned on page 366, a producer of the rotary type has been used, similarly, for carbonizing lignite by completely burning a part of the fuel and using the hot gases for carbonizing the remainder. This experiment, together with the results attained in the Bussey process, indicates the possibility of recovering valuable hydrocarbon oils in the rotary by-product producer by subjecting the incoming raw fuel to a gradual distillation at lower temperatures than can be effected in producers of the static type. By making the drum of the rotary producer longer, as has been done in the case of experimental machines, the hot gases will pass over a long bed of incoming fuel which is being constantly tumbled over and over. The initial temperature of the gases will be reduced by gradually preheating the incoming fuel to the temperature of the fire and it should be possible to make the drum sufficiently long to effect the progressive distillation of the incoming fuel at temperatures which are sufficiently graduated to avoid the destruction of valuable hydrocarbon vapors by cracking.

The efficient recovery of both ammonia and hydrocarbon by-products in a single operation should render possible the generation of producer gas at a very low cost.

Rotary Water Gas Generator.—A gas producer of this type has been operated, experimentally, as a water gas generator by

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Mech. Eng.*, March, **1920, 176.

alternate blasting and steaming. This should render possible the manufacture of water gas from cheap fuels.

THE GASIFICATION OF COAL WITHOUT DILUTION

One of the greatest needs for the efficient utilization of fuel for domestic and industrial purposes is the development of more economical methods for making gas for general distribution. The extent to which gas may be substituted for solid and liquid fuels is limited only by the price at which it can be sold to the consumer.

The processes for the complete gasification of fuels, which have already been described in this chapter, involve a partial combustion of the fuel with admission of air. The gas formed is heavily diluted with the inert gases, nitrogen and carbon dioxide. The only known and practicable way to avoid this dilution is by steaming the hot fuel in a closed retort, making water gas. The temperature must be maintained above 1,000°F.* for generating blue water gas, which has a calorific value in the neighborhood of 300 B.t.u. per cubic foot, or about twice that of producer gas. As the reaction absorbs heat, it is necessary to supply heat by a separate combustion process, in order to get rid of the inert products of combustion.

Internal Heating.—In the ordinary water-gas process this heat is generated internally by blasting the fuel charge with air, in the intervals between the intermittent blasting with steam. This process may appear somewhat crude, owing to the fact that it is neither continuous nor automatic, but requires manual control. In practice, however, this does not seem to be as great a handicap as might be expected, probably because this gas is a refined fuel which is put to high uses.

There is a more serious economic limitation in the fact that the raw materials used in the ordinary water-gas generator are usually high-grade prepared fuels. These include coke, sized anthracite and sized bituminous coal. Anthracite, being a natural prepared fuel, is too costly in most localities; while certain grades and sizes of bituminous coal have only been used to a limited extent. Most water gas is made from coke, which is a valuable prepared fuel. Moreover, most of it is enriched with oil to bring the calorific or illuminating value up to certain arbitrary legal standards, for which there is no economic justi-

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*Consult page 350.

fication at the present time. Oil is becoming scarcer and more expensive and the remaining supply is required for higher uses. Water gas should be enriched with hydrocarbon gases distilled from coal, and the calorific standards should be lowered to give sufficient latitude to allow of the use of more economical methods for making gas.*

The conventional types of water-gas generators are built like gas producers of the static type and have stationary grates. After running for several days, they are shut down and allowed to cool off, in order that the heavy formation of clinkers may be removed by hand. Most gas producers are equipped either with shaking grates or with mechanical grates. These have been tried in water-gas generators, but have not proved sufficiently satisfactory to be adopted.

As noted on page 370, the horizontal rotary type of producer (Fig. 87) has been operated as a water-gas generator with promising results. If low-grade fuels can be used for generating water gas as readily as they have been used for generating producer gas, in this type of machine, it should open up some very interesting possibilities for obtaining cheap blue gas.

External Heating.—The generation of a small proportion of water gas, in externally heated retorts, has been practised in connection with vertical retorts in plants manufacturing coal gas. This is done by steaming the incandescent charge of coke before it is discharged and quenched. In retorts of ordinary proportions, however, the rate of heat transfer through the walls and the charge is too low to maintain the temperature for gasifying more than a small percentage of the coke, the gas yield being increased about 20 per cent., while the calorific value was reduced only 8 per cent., in one instance.† This practice has only been possible since the advent of the heat unit standard, as the candlepower of the gas is reduced by about 25 per cent.

Gasification of Pulverized Fuel.—A plan for a "selective gas process" has been worked out in detail by R. H. Burdick,‡ and, while the process as a whole has not yet been tried out, the

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*This subject is discussed in Chap. VII.

†References: L. J. Willien, "Steaming Tests at Springfield, Mass.," *Gas Age*, March 1, 1919. M. G. Welsh, "Steaming Tests at Schenectady, N. Y.," *Gas Age*, Jan. 26, 1920.

‡Gas engineer, Electric Bond & Share Co., 71 Broadway, New York, N. Y.

component parts are based on well known data and the chemical reactions and heat balance have been carefully checked.

Pulverized fuel will be prepared in the usual way, but will have a small proportion of extraneous mineral matter mixed with it during preparation, to act as a catalytic agent. The materials which may be used include lime, limestone, and a number of other substances. A long inclined retort of tubular form is heated externally to maintain a temperature of about 1,800 to 1,850°F. (980 to 1,020°C.) within the walls. The fuel is injected into the upper end with a jet of superheated steam. A stream of gas is admitted near the jet, to act as a carrying medium for the pulverized fuel. This may be obtained from the supply generated in the process and preheated before admission to the retort.

As pulverized bituminous coal is carried through the retort, in suspension in the current of gas and steam, various actions and reactions take place more or less simultaneously; but for purposes of illustration they may be considered in order:

1. The individual particles are subjected to destructive distillation by the radiant heat from the walls, and by contact with them, with consequent formation of gas. A slight vacuum may be maintained in the retort. It is claimed that thus, together with the presence of the catalyzer and the rapidity of the heat transfer, will intensify the rate of distillation and the quantity of gas generated.

2. The residual product from this distillation will be incandescent particles of coke which will react with the steam and form water gas, in accordance with the reactions given on page 350.

3. Due to the nascent state of the various vapors and gases formed (and in the course of formation) and to the presence of the catalyzing agent, a further series of reactions will take place under the influence of heat within the retort, forming a series of gases of higher thermal value than the normal products of destructive distillation or water-gas production, and any tar or oil vapors formed, or in the course of formation, are converted into "fixed" gases.

4. Owing to the inclination of the retort and flow of both generated and introduced gases through it, and to the "sweeping" action of these gases, the residual solid particles (chiefly ash) will issue from the lower end of the retort, from which point they will be separated from the issuing gases and deposited in a water-sealed ash compartment below the lower end.

5. Gas as it issues from the lower end of the retort is conveyed to a suitable "seal," as in water-gas practice, thence to coal dryer, exhauster, purifying apparatus, station meter, gas holder, etc., all as in standard gas-plant practice. The remaining sensible heat of the gas will be utilized in the coal dryer.

Owing to the use of pulverized material, carried in suspension, each particle is subjected to the same individual heat treatment, with the consequence that uniformity of product is readily maintained. This is not true in present-day commercial processes wherein coal is treated in a mass and the gases and vapors are subjected to unequal temperature conditions.

The name "selective process" is intended to emphasize the point that there are a number of variable factors which may be so controlled as to obtain gas of different characteristics from the same fuel, or for adapting the process for gasifying different fuels, such as:

1. Character of catalyzer.
2. Proportion of catalyzer in mixture.
3. Temperature within the retort.
4. Proportion of steam admitted.
5. Quantity and character of gases used as a carrier.
6. Velocity of mixture in the retort.
7. Degree of vacuum in the retort.

The calorific value of the gas will depend upon the composition of the raw fuel and should range from about 540 B.t.u. per cubic foot, in the case of good gas coals, to about 300 B.t.u. for blue gas made from low-volatile fuels, such as anthracite, coke and semicoke; the latter being the carbonized residue from low-temperature distillation processes.

Plans are being made for trying out this process in an oil-gas plant in a western city. Pulverized lignite will be gasified in an oil gas generator; the same retort being used in order to utilize the existing plant while substituting solid fuel for oil. Any finely divided coke resulting from partial gasification, will be briquetted for use as domestic fuel, as is now done in the case of the residual lamp black from the oil.

The Trent Water Gas Process.—A somewhat similar process is being developed experimentally by the Trent Process Corporation.* Trent amalgam, consisting of bituminous coal and oil (page 628), is mixed with water in the proper proportion for

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* 1440 U St. N. W., Washington, D. C.

making carbureted water gas. The mixture is then pumped through a spiral coil of metal tubing which is mounted in a furnace and externally heated to a temperature of 800 to 1,000°C. at the hottest part. The mixture is completely gasified, leaving only the pulverized ash.

Blue gas can be similarly made from a mixture of pulverized anthracite and water, the coal preferably being ground in a tube mill by the wet process (page 374). A small amount of oil, added while grinding, will form a thin film on each coal particle, which will tend to keep the particles in suspension in the water until gasified. Non-coking bituminous coal, including Brazilian subbituminous coal, has also been used.

Suitable metals are available for this high-temperature service. Calorizing the outer surface will protect steel tubing from oxidation and render it suitable for withstanding fairly high temperatures. If the lower turns of the coil are to be subjected to a higher temperature, they may be cast from special alloys. Cast nichrome has been used in continuous service at a temperature of 1,150°C. in furnaces in other industries and stellite alloys are often used where similarly high temperatures are encountered.

At elevated temperatures chemical action takes place between steam and iron, the steam being dissociated with the formation of hydrogen and iron oxide. This action has been found to take place even at the temperatures of saturated steam, but the oxide forms a protective coating on the metal which soon stops the action. At high temperatures, the action is stronger and the oxide film no longer protects the iron.

In this process, however, the presence of carbon introduces another factor and the iron, apparently, is protected from the action of the hydrogen by carburization of the surface. Samples of steel tubing have been cut for examination after service in the gas generator and photomicrographs indicate the presence of a deep inner zone of cementite, or iron carbide (Fe_3C).

The reactions involved in the formation of water gas are given on pages 350 to 352. It will be noted that at temperatures of about 500 or 600°C. steam reacts with carbon to form hydrogen and carbon dioxide, while at temperatures of about 800° and upwards CO is largely formed in place of CO_2.

Gasification in Standard Generators.—The amalgam has also been successfully gasified in the standard type of water-gas generator. It is fed into the top of the generator in the form of a thin ribbon during the gas-making period, which is of 5-min. duration. The oil is completely vaporized from the amalgam during this steaming period, leaving only a coke to be partially burned during the blow. The ash content of the coal is reduced to a minimum during the preparation of the amalgam, and the residual ash in the generator is in the form of a fine powder. This is in strong contrast to the gasification of coke, which is accompanied by the formation of a considerable amount of hard clinker. The amalgam has been made from several grades of coal, including both bituminous and anthracite, and in no case has any clinker been formed. In the initial tests the gas output of the generator has been increased by approximately 66 per cent., as compared with the output when using coke and gas oil.

This process should make it practicable to utilize cheaper raw materials in the manufacture of carbureted water gas in existing installations. The amalgam may be prepared from anthracite silt, coke breeze, bituminous slack, and other cheap grades of coal. In place of using the better grades of gas oil, as at present, the amalgam may be made from heavy asphaltic base oils, base sediment, coal tar pitch, etc. As in the ordinary water gas process, some tar is produced and this may be utilized in making the amalgam. Thus it is kept in circuit until it is converted into gas and does not have to be disposed of as a by-product.

Possibilities for Continuous Processes.—The gasifying capacity of the retorts should be much greater than is the case with the retorts in the ordinary gas bench, and the investment required will be much less. The lower fixed charges should render it practicable to operate them with a variable load with less holder capacity.

These are primarily gas-making processes and will gasify all of the combustible matter in the fuel without the production of by-products. This will be a considerable economic advantage under the following conditions:

1. In localities where there are insufficient markets for all the by-products.
2. For small gas plants.
3. For plants where the load is variable.
4. For carrying peak loads where the steady load is carried by by-product plants.

By-products.—When making producer gas or water gas from raw fuels of high-volatile content, a large yield of hydrocarbon by-products may be recovered in advance by subjecting the fuel to low-temperature distillation (see Chap. VII). The carbonized residue, or "semi-coke," can then be gasified. Soft, friable or powdery varieties of semi-coke can probably be used to the best advantage for making water gas, either in the horizontal rotary producer or by pulverizing for use in the continuous processes.

An interesting possibility suggests itself in connection with the Trent process and that is the recovery of the nitrogen content of the coal in the form of ammonia or ammonium sulphate. This process lends itself to more accurate control of temperatures than can be expected in a gas producer and the conditions should be more favorable for a high percentage of recovery. Even if the operating temperatures required when making water gas for general distribution prove high enough to dissociate ammonia, it should be practicable to make a lean gas for boiler fuel at a lower temperature. This would correspond to by-product producer gas, but hydrogen would be the predominant combustible constituent with CO_2 as a diluent.

Synthetic Methane.—It has been found possible to make methane (CH_4) from blue gas synthetically in the presence of a nickel catalyzer.* This has been done experimentally with a view to enriching blue gas for mixing coal gas. The reactions take place at moderate temperatures between hydrogen and carbon monoxide or dioxide. With CO_2 gas, the reaction occurs between 230 and 300°C., being as follows:

$$CO_2 + 4H_2 = CH_4 + 2H_2O.$$

With CO gas, the reaction occurs between 180 and 250°C., as follows:

$$CO + 3H_2 = CH_4 + H_2O.$$

At temperatures above 250°C., the latter reaction is complicated by a further reaction which deposits free carbon on the catalyst and tends to render it inactive:

$$2CO = CO_2 + C.$$

This carbon deposit can be reduced with a blast of superheated steam at a temperature of about 450°C., with the formation of carbon dioxide and hydrogen. The CO_2 in turn interacts to form methane.

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* See "Catalytic Methane from Blue Gas," by MARK MEREDITH, of Liverpool, England, *Gas Age*, Jan. 10, **1921**, 7.

In practice, these gases are not present in the proper proportions in ordinary blue gas. Also, any sulphur compounds present may effect the catalyzer. The latter may also be attacked with the formation of nickel carbonyl.

With new methods available for making blue gas rich in CO_2, some of these limitations may be avoided, and an excess of CO_2 may be removed by solution in water.

PEAT AS A GAS-MAKING FUEL

Excavation and Drying.—In some parts of the United States and Canada that receive their coal supply by long transportation routes from distant coal fields, large deposits of peat are available. Peat, as it lies in the bog, contains 85 or 90 per cent of moisture, and the heat required for its evaporation is practically equivalent to its thermal value after drying. Taking the average moisture content as 87.5 per cent, 7 tons of water must be eliminated to obtain 1 ton of theoretically dry peat. It may, however, be slowly dried in the air to a moisture content of from 20 to 60 per cent., and may then be gasified in producers of either the Lymn or the horizontal rotary types.

These last 1 or 2 tons of moisture are evaporated much more slowly, during air drying, than the first 5 or 6 tons with which a ton of theoretically dry peat is originally saturated. This fact, together with the necessity of handling such a large amount of material, has hindered the use of peat in competition with coal.

In Europe, where labor is cheap, peat has often been dug and handled manually. Various complicated combinations of machinery have also been used. One of the most practical suggestions that has been made for excavating peat is the use of suction dredges, but these are applicable only to large bogs which can be kept flooded.

The author has tried some simple experiments in pouring a small stream of water on freshly dug peat and found that it may be readily disintegrated and converted into a wet sludge. This suggests the possibility of excavating peat from any kind of bog, by means of hydraulic sluicing, during periods when a sufficient water supply is available. This procedure would be similar to the hydraulic mining of gold-bearing gravels in the western States, except that smaller jets of water should suffice. Sluicing will wash out miscellaneous materials contained in peat, such as mineral matter and solid vegetable matter, and will leave them behind. This will simplify the clearing of the surface of the bog and will recover one salable by-product at the start; *i.e.*, peat litter. This consists of the softer living vegetable matter, such as mosses and root fibers, which are useful as bedding material for live stock.

The sludge can be pumped through pipes to the gas plant, which may be located in a place which is suitable for a power station. The location may allow of receiving coal by rail, as an auxiliary fuel for use during the months when drying is not possible. Peat, however, should be stored for winter use if practicable. The location should also have a large area of level land for drying. A possible method would be as follows:

Long parallel gravel dikes could be built and crane rails could be laid on their tops. The cranes would span the wide intervening ditches which would be used as settling basins. They would be filled with sludge and the clear water drained off through overflow pipes. The cranes would carry machines for excavating ditches in the surface of the peat for drainage purposes. Longitudinal ditches could be dug a few feet apart, with occasional cross ditches to carry off water. The wet peat from the ditches might be piled on the ridges in such a way as to give the surface a gentle slope for shedding rain water. The crane might also carry harrows for breaking up the surface to allow the top layer to dry by evaporation. Finally, the crane would carry apparatus for removing the top layer and conveying it to storage piles. These might be covered with tarpaulins to protect them from rain.

Where there are several bogs in the vicinity of the plant, they may all be utilized in succession by this method. Most of the machinery will be centralized at the plant and the only machinery which need be moved around the bog will be some electrically driven pumps. Where peat bogs are located near navigable lakes or rivers, the peat may be dredged and loaded in scows. These will be towed to the plant and the peat may be removed by disintegrating it with water jets and pumping the sludge into the settling ditches.

Some localities where peat may be used with good advantage, to reduce the importation of coal from a distance, are: Quebec, Ontario, Manitoba, Minnesota, the New England States and Florida. The latter state has the important advantage of being able to dry peat during practically all seasons of the year. In most parts of North America, however, the expense of air drying will offer a rather serious limitation to the substitution of raw peat for coal. It would, therefore, appear preferable to prepare peat for gasification by the wet carbonizing process.*

The Wet Carbonization of Peat.†—Peat bogs are distributed all over the surface of the earth and represent enormous deposits of carbon. Based upon Geological Survey Reports giving the area and depth of bog land, it has been estimated that there is more carbon in the peat deposits than in all known coal fields. The excavation, handling and draining of peat have been discussed on pages 378 to 380, and the difficulties incident to air drying have been mentioned.

The mechanical pressing out of water from peat has frequently been suggested, and experiments on a small scale with surface peat have given positive results; but the black fuel-peat, which predominates in peat deposits, does not give off its water when submitted to pressure.

Ekenberg claimed that "the reason that the water does not separate under pressure is because of the presence of a slimy hydrocellulose, produced from the residues of the decaying plants of which mature peat consists. This hydrocellulose is formed by prolonged contact of the cellulose with water. It is

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* The above method of drying (pp. 378 and 379) is based on a method which was developed in Canada for the drying and pneumatic collection of peat from the surface of a bog. (Consult *U. S. Bureau of Mines*, *Bull.* **16**, 1911, "The Uses of Peat," by C. A. Davis, p. 113.) This method, however, involved the expense of laying tracks over the surface, as well as the clearing of wooded bogs. The author as modified the plan to centralize the operation in connection with excavation by hydraulic sluicing. The latter operation should also be useful in connection with wet carbonization.

Publications of the Fuel Research Board, of the Dep't of Scientific and Industrial Research (16 & 18, Old Queen St., Westminster, S. W. I., England), relating to peat:

"The Winning, Preparation and Use of Peat in Ireland."

"The Carbonization of Peat in Vertical Retorts." (*Tech. Paper* No. **4**).

Publications of the Canada Dep't of Mines, Mines Branch, Ottawa, relating to peat: No. **154**, "Utilization of Peat Fuel," by B. F. Haanel, 1910–1911; No. **299**, "Peat Lignite and Coal," by B. F. Haanel, 1914; No. **477**, "Peat Fuel for Generating Steam," by J. Blizard, 1917; Nos. **30, 151, 266** and **351**, "Investigations of Peat Bogs and Peat Industry of Canada," 1909–1915.

† Largely from paper by M. Ekenberg, of London, England, "Fuel from Peat," Iron and Steel Institute, May 14, **1909**.

present to the extent of 0.2 to 1.2 per cent, and more, of the peat substance, and can be extracted from the peat. It readily forms dextrose, and is destroyed by heating in the presence of water to temperatures above 150°C."

He has examined numerous peat samples from different parts of the world, and found that they all contain this hydrocellulose. "The greater the percentage present" the more difficult it becomes to separate the water. The isolated hydrocellulose has remarkable properties. In peat it is enormously swollen, having taken up water and formed a jelly of the consistency of soft soap. A jelly containing 25 times its own weight of water is still comparatively stiff, and can be cut into slices. If the jelly be pressed in a canvas bag, it passes unchanged through the meshes without separating water. Submitted to pressure, it transmits the pressure in all directions like a homogeneous solution. A pulp from mature peat submitted to pressure also passes unchanged through the meshes of ordinary canvas with holes of about 1 sq. mm. If, however, the hydrocellulose present in the raw peat-pulp is extracted or destroyed, the bulk of the water can easily be separated from the plant residues by pressing the peat in a canvas bag, or against a suitable metallic grating. If such pressable peat be mixed with a small percentage of slimy hydrocellulose and water to the amount of that contained in raw peat, it again becomes impossible to separate the water by mechanical pressure, the pulp going right through the meshes.

"It is this hydrocellulose which binds the particles together in the peat-sods obtained when making air-dried peat in the usual way. Under the microscope the hydrocellulose can be seen as a jelly, on staining the preparation with fuchsine or methylene blue.

"A typical mature fuel peat appears as a mixture of a few fibers embedded in a preponderant mass of broken-up plants in a more or less decayed state. The cells are filled with, and surrounded by, a gelatinous or slimy substance, which is the hydrocellulose. The surface peat, however, appears as fibers of various kinds with large cells. But little, if any, slimy hydrocellulose is found in surface peat.

"When it had been ascertained that a substance of the nature of hydrocellulose prevented the water from being pressed out of peat, there was comparatively little difficulty in devising a treatment by which the separation of water could be technically effected, the hydrocellulose having been found to be destroyed by heating. By increasing the temperature of heating, other changes also take place. Thus, the percentage of carbon in the peat gradually increases with the rise in temperature, and a portion of the components—hydrogen and oxygen—combine to form water. The difference between this carbonizing process and the ordinary dry-charring in retorts is the presence of fluid water. The heat is transmitted by the water which surrounds every peat particle. Water is a much better conductor of heat than gas, allowing a sharply defined charring with a uniform effect, corresponding exactly to the temperature used."

Since the required temperatures range from 155° to possibly 200°C., the heating is done in closed vessels and under pressure. The specific heat of the pulp is about 0.92, so that regeneration of the heat is necessary for economical operation. The pulp may be forced through a tubular regenerator with an ordinary sludge pump. Ekenberg found that from 57 to 65 per cent of the heat applied could be regenerated; and the higher the temperature of carbonization, the greater is the efficiency of regeneration. The carbonization is instantaneous, so that the time required is only that necessary for heating the pulp.

Installation near Dumfries, Scotland.*—In a recent installation near Dumfries, Scotland, peat, containing as high as 93 per cent of water, is first made into pulp and then forced under high pressure through 2-in. steel tubes heated by steam jackets. After the peat has been wet-carbonized, it is forced, under a pressure of 120 lb. per square inch, into filter presses, where the water content is reduced to about 25 per cent. The peat cakes are then pulverized, and the dust is blown through boiler flues and dried to 2 per cent. moisture content. It is then pressed into briquets weighing from 0.5 to 1.5 lb., with a calorific value of 11,200 to 12,500 B.t.u. per pound.

Products.—It is evident, from this, that wet carbonization can be used for the preparation of peat for either gasification, pulverizing or briquetting. The first crude product, in the form of filter cakes, contains only a little more moisture than raw peat which has been thoroughly air dried to a moisture content of 15 or 20 per cent., and considerably less than peat which has been dried in wet summers in Europe, when the moisture content often cannot be reduced below 33 or 40 per cent. This process is

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* *Chemical Eng. & Mining Rev.*, **12**, (1919), 76–9;
J. Am. Peat Soc., Jan., **1921**, 31.

independent of the season and it reduces the various types of peat, both young and mature, to a product of more nearly uniform properties and fuel value.

The Ekenberg Process.*—In the absence of further information in regard to the Dumfries plant, we shall review briefly the original process, as developed by Ekenberg in Sweden between the years 1904 and 1909.

The peat was dug and then thoroughly macerated by mechanical means at the bog. The macerating machine delivered the pulp to dumping cars which carried it to a storage tank. The wet-carbonizing apparatus consisted of 52 iron pipes, 36 ft. in length. Within each pipe was a rotatable inner tube which carried a worm upon its outer surface. The raw peat was forced into the annular space at the cold end of the tubes by a sludge pump, under a pressure of 150 lb. per square inch, and was kept moving toward the hot end by the rotation of the worms without the loss of its initial static pressure. The tubes were heated in a furnace, into which they projected for about one-half their length. The outer tubes were closed at the hot end and the carbonized peat returned through the inner tubes, giving up its sensible heat to the incoming pulp.

The maximum temperature to which the material was subjected was about 155°C., and the pressure used was sufficient to prevent the volatilization of either the moisture or the hydrocarbons. The peat became blackened and fine grained, losing its structural peculiarities. By the use of higher temperatures and pressures more complete carbonization was effected.

Gasification.—The press cakes should make an excellent fuel for the by-product gas producer, while the carbonized pulp could even more readily be prepared for gasification by the Trent water-gas process. It is already finely divided and only enough water need be pressed out to leave it with the proper amount for making water-gas. If pulverizing would be required, it would be only a minor operation. Moreover, it might be possible to effect gasification at a lower temperature than would be required in the case of coals of more mature rank. This should be favorable to the recovery of ammonia. Peat is under a disadvantage in competing with coal when it must be prepared in solid form; in this instance, however, the advantage should be in favor of peat localities where it is available.

* Condensed from *U. S. Bureau of Mines, Bull.* **16**, pp. 123 to 125.

Briquetting and Distillation.—The press cakes should make an excellent material for distillation at low temperature, especially where carbonized fuel is wanted in localities where peat is available. The following data indicate the results obtained by briquetting and distillation at high temperatures.*

Briquets.—The appearance of a briquet of wet-carbonized peat is very similar to that of a lignite briquet. It has a black glossy surface, and is very compact. During the wet carbonizing, a wax of paraffinaceous nature is liberated, which serves as a binder for the particles. There is 3 to 4 per cent of this wax in wet-carbonized peat. For practical purposes, the briquets can be regarded as impervious to water.

The briquets from wet-carbonized peat burn with a long luminous flame and are quickly lighted. Thin pieces can be lighted with a match like wood. With an ordinary chimney draft they burn without soot or smoke. A fire of briquets is more like a wood fire than a coal fire.

The specific gravity of the wet-carbonized peat briquets varies from 1.29 to 1.35. Owing to saving of space by the regular shape of the briquets, the volume weight is considerably higher than in the case of coal. Bulk for bulk, there is no difference in heating value between the briquets and ordinary coal.

Ekenberg has described two types of products which were made by the dry carbonizing of the briquets. Rapid heating produced a light porous product, similar in appearance to wood charcoal, which he called "peat charcoal." Slow heating produced a hard dense "peat coke" with smaller pores than ordinary coke. Slow heating allowed time for the gases to escape and resulted in a coke having a weight of from 30 to 32 lb. per cubic foot (47 to 51 kg. per hectoliter), while coke from ordinary coal showed weights of from 36 to 45 kg. per hectoliter. The coke has a high-crushing strength—from 3,270 to 5,645 lb. per square inch (230 to 357 kg. per square centimeter).

The calorific value of the charcoal and coke were as follows:

	B.T.U. LB.	CAL. KG.
Charcoal	13,700–14,000	7,600–7,800
Coke	13,140–13,880	7,300–7,700

Wet-carbonized press cakes distilled in a retort at high temperature gave 17,472 cu. ft. of crude gas per ton, with an illu-

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* Reference *cit.* on p. 380.

minating power of 15 sperm candles. The yield of coke was 33 per cent. After the gas was purified with potash, the yield was 14,851 cu. ft. of 20 candlepower. The gas was practically free from sulphur.

Economic Limitations.—B. F. Haanel* states that efforts are still being made to adapt the wet-carbonizing process to the manufacture of fuel on a commercial scale. The development, however, has been delayed by economic limitations in connection with the removal of moisture, owing to the fact that it has been found difficult to remove a sufficient proportion of the water by pressing. Hence, a considerable amount of moisture is left to be removed by heat.

The hydrocellulose is a colloidal substance which occurs in all humified peats to a certain extent and, like gelatine, possesses an enormous capacity for absorbing water. The destruction of the colloidal properties of this hydrocellulose, however, does not perceptibly affect the capacity of the peat for absorbing water. The fact is that the better and older humified peats are themselves of a colloidal structure, or at least possess colloidal properties which limit the amount of water that may be removed by pressing, even after the destruction of the hydrocellulose. While, as a result of carbonizing, the altered peat does submit more readily to pressing, the increased quantity of water which can thus be separated is, in Haanel's opinion, not sufficient to enable this process to be conducted commercially. This statement probably refers to the production of solid or pulverized fuel, rather than to the drying of peat for gasification. Haanel states that, for gasification in the by-product producer, the moisture content should preferably not exceed 35 per cent. At the wet-carbonizing plant near Dumfries, Scotland, it is claimed that the product contains only 25 per cent. of water. In the Trent process for the gasification of mixtures of pulverized coal and water in an externally heated tube, it would probably be advantageous to use peat containing from 60 to 75 per cent. of water. In either case, the wet-carbonizing process should offer a useful method for the removal of the excess moisture without the necessity for drying by evaporation.

Press cakes containing a relatively large proportion of residual water could be successfully gasified in a new type of producer which is being used in Germany. The raw fuel is passed through

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* Reference cited on p. 380.

a low temperature retort, while being fed into the producer, and the moisture would be evaporated by the hot producer gas which is drawn through the fuel in the retort. A somewhat similar action takes place in the horizontal rotary producer when the hot gases pass over the incoming fuel.

It is of interest to note that several products are obtained from the gasification of peat in the by-product producer which have not been obtained from coal, either by gasification or by distillation at low temperature. These include methyl alcohol, acetic acid and acetone. Methyl alcohol is now obtained only from the gasification, distillation or other treatment of wood and wood waste. Acetic acid is now obtained from the distillation of wood, by bacterial oxidation of vegetable matter, or by the oxidation of acetylene. Acetone is obtained from acetic acid by the distillation of calcium acetate. The gasification of peat should make these products available at a lower cost than they can be produced by the hard wood distillation industry which is the main source at present.

GAS-FIRED BOILERS*

Having reviewed the methods of gasifying fuels, with particular reference to the production of cheap gas for power purposes, it remains to be seen how the gas may be utilized efficiently for generating steam.

When producer gas is generated in one place and burned in another, we have fires in two places and thermal losses in each. In the producer, the losses may range from 20 to 33 per cent., and, when gas is burned in a large furnace under a boiler, there is a loss of similar magnitude. The net efficiency of these two fires, therefore, may range from 45 to 65 per cent., or thereabouts. The disadvantage of having two furnaces can be partially offset by burning the gas in the tubes of a cylindrical type of boiler, thus avoiding losses by radiation from the furnace and by leakages through the brickwork.

A number of methods have been tried for intensifying the combustion and for increasing the rate of heat transfer per unit of area of the tube walls. These involve the insertion of refractory materials in the tubes which become incandescent and

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* Consult also "Firing Steam Boilers Without Flame," by W. A. Bone and P. St. G. Kirke, *Sci. Am. Monthly*, March, **1920**, 3248. This article is reprinted from the *Journal of the Society of Chemical Industry*, **38**, 228T.

radiate heat to the walls. One of the earlier methods involved the application of the "surface combustion" principle, as presented by W. A. Bone. This process of burning gas consisted in the introduction of a mixture of gas and air, in proper proportions, into the voids of a mass of granular refractory material. The gases spread out after entering the voids and slowed down to the velocity of propagation of the flame. The fire would travel back, until it met a mixture coming toward it at this velocity and combustion took place in the voids without visible flame. The granular material was heated to incandescence and intensified the combustion of the gas in contact with the hot surfaces.

This method was first applied to the firing of boilers in England, the granular material being placed in the vertical tubes of the "Skiningrove boiler."* The gas was burned with very high efficiency, but the resistance of the granular material in the tubes required a high fan pressure to force the gases through the mass. Another limitation lay in the fact that the pieces of material adjacent to the walls of the tube could get rid of the heat generated on their surfaces, by radiation, but the material in the interior could not. In the case of large tubes, the material in the center would fuse and this limited the application to tubes not larger than 3 in. bore. The output of the tubes was limited to 50 lb. of steam per hour, and the gas could contain but very little dust, owing to the liability of choking the voids. Another difficulty was that the mixing of the gas and air took place before combustion commenced. This necessitated the introduction of an explosive mixture through a refractory inlet, at high velocity, to prevent backfiring. If there was a wind, if the suction dropped, or if the mixture was incorrect, backfiring took place into the mixing tube, necessitating continual attention.

The Bonecourt Boiler.—Surface combustion, or a modified form of this principle, has more recently been applied in England to the Bonecourt boiler. This is a cylindrical type of boiler, and the gas and air are introduced into the tubes separately, and not as an explosive mixture, in accordance with U. S. Patent No. 1319226, issued to P. St. G. Kirke, 1919.†

The first method used commercially involved the use of

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* Consult article on surface combustion, *Ann. Report Smithsonian Inst.*, 1913.

† See U. S. Patents 1279710 and 1321056; other applications pending. British English Patents 17842 and 124016 cover the same principles.

moulded rectangular blocks of refractory material which corresponded in length with the diameter of the tubes. These blocks were arranged in a spiral by rotating each one through a small angle with respect to the adjacent blocks. The spiral was maintained in position by means of rods which set in grooves in the ends. There were two clear passages for the gas which could contain a considerable amount of dust without detriment. The gas burned in contact with the hot surfaces, at a highly accelerated rate, and the heat was radiated freely to the walls of the tube. This allowed of the use of tubes up to 6 in. in diameter and 13 ft. in length, the refractory block extending for about one-third the length of the tubes. A straight bar of material was used in the remaining length which was heated by the gases and radiated to the walls in sufficient degree to increase materially the rate of heat transfer from the products of combustion to the water.

In the latest type of Bonecourt boiler, the refractory blocks have been replaced by a spiral packing of cast iron, which resembles an auger bit in shape. Owing to the fact that the boiler tubes are only a few inches in diameter, and also to the fact that the heat developed on the surface of the packing can radiate freely to the water-cooled tube walls or be transferred by conduction, the average temperature over the packing varies from 650 to 500°C., while the maximum temperature attained for a short distance from the inlet end of the tubes hardly exceeds 800°C. Consequently, cast-iron packing at the inlet end and wrought-iron elsewhere have been found quite satisfactory in practice and are mechanically sound. The exhauster which is used on the larger boilers causes the products to pass through the tubes and over the packing at a sufficiently high velocity to ensure any dust being carried right through the tubes.

Each tube is provided with a special burner giving a jet of gas, which is supplied under a presure of ½ in. or more of water, and this aids in inducing the air required for combustion. The mixture is not completed until the gas reaches the packing, which commences a short distance within the tube and is plainly visible to the operator. In lighting the fire, a slight excess of gas is turned on at first, then the mixture is adjusted to maintain the packing at a maximum temperature. No backfiring can occur, and any explosion which may take place is limited to the mixture of gas and air in a single tube, which renders this type of boiler much safer than if the gas were burned in a large furnace, or if an explosive mixture were fired in accordance with the original surface-combustion principle. In another form of burner, known as the regenerative burner, the initial gas jet induces a part of the air required for combustion by drawing it into a primary mixing chamber. The initial mixture is so rich that backfiring cannot occur and it issues from a nozzle at the end of this chamber into a short open gap and is then drawn through an orifice in a refractory plug, in the end of the boiler tube, by the suction caused by the exhauster. A space is provided between this plug and the end of the packing, inside the tube, which forms a secondary mixing chamber. The secondary air supply, required for combustion, joins the primary mixture while the latter is crossing the gap and the final mixture is drawn through the orifice at an accelerated rate.

Possibly 10 per cent. of the combustion occurs by flame between the orifice and the packing, most of the remainder taking place in the length of the first 3 ft. or so of the incandescent packing. The spiral motion of the gases causes them to scour the surface of the tube and sweep away any inert film of gas such as tends to interfere with the transfer of heat in tubes where the flow of the gases is parallel with the walls. It is claimed that this method of burning gas enables the average evaporation, per unit of heating surface, to be increased 400 per cent. above ordinary practice.

It is evident that the sub-division of the combustion among many tubes ensures a thorough mixing of the gas and air; consequently, 10 per cent. excess air has been found to be ample. It is claimed that it is not possible to secure correspondingly thorough mixing in large boiler furnaces.

One factor which enables the attainment of high rates of evaporation, per unit of tube surface, is the free circulation of the water in the cylindrical boiler and the fact that most of the steam is disengaged at the hot end. In the first type of Bonecourt boiler, when refractory blocks were used as packing, from 60 to 70 per cent. of the evaporation took place on the first third of the length of the tubes, where the average rate was 42 lb. of steam per square foot, the average for the whole tube being 20 lb. This evolution of steam tends to accelerate the circulation at the hot end of the boiler, the water flowing downward at the cooler end. The steam is taken from the cool end and is remarkably dry.

To facilitate cleaning, the tubes are arranged in vertical banks separated by spaces for a man to stand in. With many kinds of water, scale forms to a thickness of about a millimeter and then flakes off and drops to the bottom, where it may readily be blown out each day. These factors all render it practicable to force the boiler with safety.

Table XLII is the record of a test on an unlagged Bonecourt boiler fired with coke oven gas and equipped with a feed-water heater. Approximately 5,000 lb. of steam were generated per hour (from and at 212°F.). The efficiency of 92.7 per cent. is figured with relation to the net calorific value of the gas.

TABLE XLII

Gas burnt in cubic feet	112,030
Steam raised from and at 212°F. in pounds	49,800
Cubic feet of gas per pound of steam, from and at 212°F.	2.25
Duration of test in hours	10
Steam temperature at 100 lb. pressure, degrees Centigrade	170
Temperature of the gases leaving the boiler, degrees Centigrade	198
Difference of temperature between the steam and the products leaving the boiler, degrees Centigrade	28
Temperature of the gases leaving the feed-water heater, degrees Centigrade	95.7
Dryness of steam, per cent.	99.3
EFFICIENCY (unlagged), per cent.	92.7

TABLE XLIII

Diameter of shell, feet	Length of tubes, feet	Suction in inches of water	Maximum evaporation from and at 212°F. per hour			
			With coke oven gas		With producer gas	
			With economiser	No economiser	With economiser	No economiser
8½	18[1]	10[1]	40,000	30,000	32,000	24,000
6	18[1]	10[1]	20,000	15,000	16,000	12,000
4	18[1]	10[1]	10,000	7,500	8,000	6,000
4	13½*	6[1]	7,500	5,600	6,000	4,500
4	9	2½	5,000	3,700	4,000	3,000
3½	8	2	......	3,000	......	2,000
3½	4	Natural draught	......	1,500	......	1,000
1¼	4	Natural draught	......	125	......	90

* NOTE.—The amount of suction depends for a given output upon the length of the boiler shell. Both suction and length of shell can be reduced to any desired extent by increasing the diameter of the boiler. This, however, adds considerably to the cost.

Table XLIII gives some data on a few representative sizes of this boiler when burning rich and lean gases. These boilers are also built for burning fuel oil.

The superheaters and economizers are of cylindrical form with horizontal tubes for the hot gases which also contain the patented packing. The same general type of construction is used in Bonecourt waste-heat boilers which are used for recovering the sensible heat from the flue gases in industrial furnaces and from the exhaust gases from gas engines.

POSSIBILITIES FOR FURTHER RECOVERY OF HEAT FROM BOILER-FLUE GASES

One of Kirke's patents also covers the principle of preheating the air for combustion, with the waste heat in the flue gases, in connection with the Bonecourt type of boiler. It would seem reasonable to expect that the lower rate of evaporation possible with lean gas (Table XLIII) can be increased by preheating the air.

The products from the combustion of most gaseous fuels contain a considerable proportion of moisture which does not condense until the gases have been cooled below 212°F. There is, therefore, a disproportionate amount of heat available, from the latent heat of this moisture, as it condenses at the lower temperatures. The preheating surface may be so limited as to discharge the flue gases at a sufficient temperature to avoid condensation and, at the same time, to provide a temperature gradient, in excess of 150°F., for effective heat transfer between the dry gases.

Most of the remaining heat may be recovered by a water heater, including the latent heat from the condensation of the moisture. This may be used for the preliminary heating of the feed water and will not be under pressure. The final heating of the feed water may be done in a direct contact heater with steam from a single-stage house turbine exhausting at a suitable intermediate pressure, such as 60 or 80 lb. above the atmosphere. The temperature of the exhaust steam at these pressures is 307 and 324°F., respectively, which should permit of heating the feed water reasonably near to the temperature in the boiler, which is 388°F. at 200 lb. pressure.

Utilizing Low-temperature Heat.—In a by-product producer plant of the Lymn type, the preliminary heating of the feed water may be done in the producer tops (as mentioned on page

346), where it may be raised to about 170°F. By-product producer gas has a high content of hydrogen, which produces a large amount of water vapor during combustion. The water heater, therefore, may recover a considerable amount of low temperature heat, which represents the latent heat of the steam and moisture originally used for saturating the air blast for the producers.

In large plants it may be possible to utilize this heat for generating steam for operating turbines at pressures below the atmosphere.

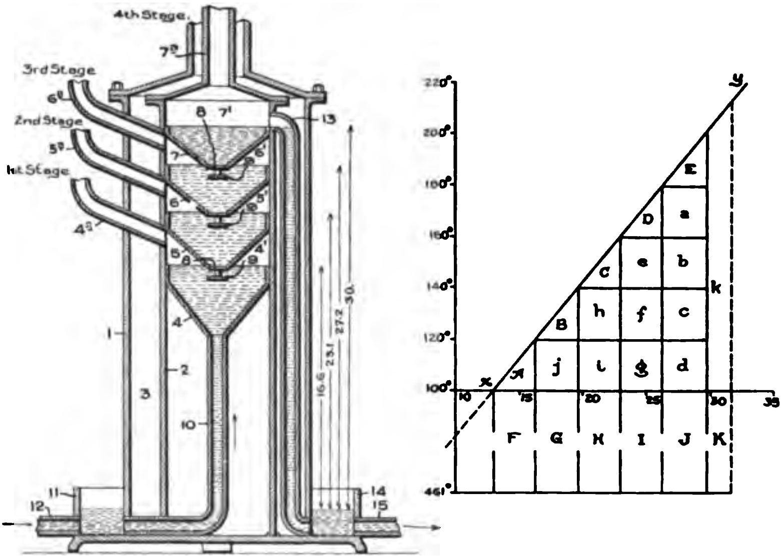

Fig. 86.—Low-pressure steam generator (F. P. Coffin, United States Patent 1,105,405, July 28, 1914).

Figure 86 shows an apparatus designed by the author (U. S. Patent No. 1105405 of 1914) for generating low-pressure steam from hot water for the production of power with a maximum thermal efficiency. It consists of a barometric water column, which expands into several hopper-shaped receptacles (Nos. 4 to 8), allowing the steam to be disengaged over wide surfaces at each of several pressures. The steam is piped to the nozzles of the different stages, in a specially designed turbine, at the several successive pressures (Nos. 4*a* to 7*a*). From chamber (7) an overflow pipe (13) descends to a hot well (14) at the bottom of the apparatus, in which the water stands at the same level as in tank (11). An escape pipe (15) carries off the surplus water to be reheated.

Figure 86 is a temperature-entropy diagram, illustrating the thermodynamic principle involved in the case of a four-stage steam generator and turbine. The temperature range of operation is assumed to be from 200 to 100°F., with a drop of 20° per stage. The corresponding barometric heights of the four water columns are indicated by the dimensions at the right of Fig. 86, which are in feet. Since the liquid heating curve xy is nearly a straight line, the diagram may be divided into approximately equal rectangles and triangles for each stage.

The rectangles a to j represent most of the available energy of the steam, while the triangles A to E represent energy which would be available in a piston engine, or in a turbine with an infinite number of stages, but 97 per cent. of which goes to the exhaust in this case. Here the actually available energy is

$$\frac{10}{12.5} + 0.03\,\frac{2.5}{12.5} = 0.815$$

of the energy theoretically available over the given range. The available energy per pound of steam per stage is 24 B.t.u., which should give a jet velocity of 1,100 ft. per second and allow the use of one turbine wheel per stage. The first stage utilizes the energy represented by the rectangle a; the second stage, rectangles b and e, and so on.

The rectangles F to K represent heat going to the condensing water. The theoretical thermodynamic efficiency is 7.5 per cent. when cooling the water in the steam generator by evaporation from 200 to 120°, at which temperature it returns to the heater.

The availability of such methods for utilizing low temperature heat should make it possible to reduce to a minimum the thermal losses incident to the generation and burning of producer gas and should place it more nearly on a competitive basis with raw coal. Then the recovery of by-products, in connection with the generation of producer gas, will be sufficiently profitable to discourage the burning of raw coal where this system can be economically applied. This will be especially true in connection with the fuel supply for carrying the base load in electric power systems, where the gas plant may be kept in continuous operation.

Hot Springs.—This method should also be applicable for the generation of power from natural sources of hot water, including hot springs and artesian wells in volcanic regions. Also, for utilizing solar heat in arid regions, through the medium of water heated by the sun's rays.

CHAPTER VII

THE DISTILLATION OF COAL AT LOW TEMPERATURES

BY

F. PARKMAN COFFIN*

The destructive distillation of coal decomposes it into several types of products which vary considerably, both in composition and in quantity, according to the temperature used and the manner in which the heat is applied.

The primary products are:

1. Hydrocarbon gases.
2. Hydrocarbon vapors.
3. Hydrogen gas.
4. Inert gases.
5. Ammonia gas.
6. Carbonized residue.

The economic side of the distillation of bituminous coal at high and low temperatures, respectively, has been discussed in Chap. V (pp. 285 to 286 and 288 to 291). The terms "distillation" and "carbonization" are used more or less synonymously, according as the process is viewed from the multiple-product basis or primarily with reference to the main product, carbonized fuel. The term "carbonization" is used more or less synonymously with "coking" in connection with the high-temperature process, and in England it is used in connection with the low-temperature process as well, probably because its early history is identified with the efforts of English engineers and chemists to produce smokeless fuel.

In the United States, however, the low-temperature process is more generally viewed from the multiple-product basis and the term "low-temperature distillation" is used.

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* Research Laboratory, General Electric Co., Schenectady, N. Y.

HISTORY AND RESEARCHES

A comprehensive review* of the history, theory and practice of "the low-temperature carbonization of coal" by Edgar C. Evans, is reprinted below in condensed form. This contains a brief account of the best known processes which have been experimented with in Great Britain.

History.—The question of the low-temperature carbonization of coal is not a new one; the disadvantages of bituminous coal as a fuel have been recognized from very early times, and as far back as 1656 Evelyn described in his diary a project by Sir John Winter of "charring seacoale, to burn out the sulphure and render it sweete." The resulting "cinders" made a "cleare pleasant chamber fire, depriv'd of their sulphure and arsenic malignity."

In 1681, a patent was taken out by Becker and Serle for the production of pitch, tar and smokeless fuel from coal, while the Earl of Dundonald took out in 1781 a patent for making pitch, tar, oils, cinders, etc., from coal.

The early literature of the gas industry, from 1792 onwards, teems with references to low-temperature carbonization, but the gas engineer's desire for the utmost yield of gas from his coal led to the adoption of higher and still higher temperatures, until today the highest possible temperatures compatible with the nature of the retort are universally used in this industry.

From the point of view of the gas industry, with gas as the primary product, this choice has been thoroughly justified by the results obtained and the same thing can be said of the coking industry, where a hard metallurgical coke is the main desideratum.

Neither gas coke nor metallurgical coke, however, is an ideal substance for use as a domestic fuel, and in the modern sense of the term, the idea of low-temperature carbonization is the outcome of attempts that have been made to produce a smokeless fuel from bituminous coal.

In this sense, low-temperature carbonization can be said to date from 1890, when the late Col. Scott Moncrieff suggested the withdrawal of the charge from gas retorts when half the usual quantity of gas had been evolved, with the idea of using it as a domestic fuel. It was found, however, that the only result

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* From the *J. Soc. Chem. Ind.* (England); reprinted in full in the *Sci. Am. Supp.*, Oct. 19, 1918, 254.

was the production of a partially coked layer on the outside of the charge with an inner core of practically raw coal.

A more feasible suggestion was made in the same year by Parker, who proposed (Eng. Pat. 67, 1890) to produce a smokeless fuel by passing steam, water-gas, or coal gas, superheated to a temperature of 600 to 650°C., through a mass of coal in a retort. The idea of using an inert gas as a heating medium is an excellent one, but it failed in this as in subsequent attempts owing to the peculiar nature of the phenomena connected with the carbonization of coal at these comparatively low temperatures.

In 1906, Parker took out his famous master patent (Eng. Pat. 14365, 1906) for the production of "coalite" by heating coal in the presence of steam to a temperature not exceeding 800°F. A number of retorts were tried, details of which are given in a series of patents taken out between 1906 and 1911. The first proposal was to use D-shaped retorts, about 5 ft. wide, 7 ft. long, and 16 in. high, the coal being placed in a layer not more than 6 in. thick.

Coal which melted under heat was treated in tapering cylinders about 10–12 in. in diameter, one end being perforated to allow the escape of the gases produced, or it was heated in completely filled tubes of not more than 6 in. diameter.

These experiments failed, however, and the next step was to use a narrow vertical retort of oblong cross-section, which again was replaced by bunches of vertical tubes, each tube being from 4 to 6 in. in diameter, and each separate battery of tubes being connected by means of a separate pipe with the hydraulic main. In the later patent, these tubes were provided with slots, by means of which communication was established between adjacent tubes, so that, if one of the tubes became temporarily choked, the gas evolved could pass up the other.

This gradual alteration in the design furnishes an interesting commentary upon the difficulties experienced by the coalite company, and these proved so great that, despite the assistance of some of the best scientific brains of the country, and the expenditure of large sums of money, the process failed to satisfy commercial requirements.

The coalite failure, however, served one good purpose—it created a popular interest in coal carbonization, it showed the need that existed for a free-burning smokeless fuel, and cleared up many obscure points in coal carbonization.

A considerable amount of work has since been performed on low-temperature carbonization, both from a scientific and a technical standpoint, and while commercial success has yet to be realized, a number of the problems involved have proved capable of solution on a semi-commercial scale.

The question of commercial success by any system capable of general application is not an easy one. The process of coal carbonization itself is a most complicated one, and it is rendered still more complex by the wide differences that exist between different coals.

Low-temperature Carbonization.—In its main essentials, the process of low-temperature carbonization proceeds along similar lines to the actions which take place in the high-temperature process; but several of the factors involved are so intensified that a radical alteration in the design of the oven is necessary for the process to be carried out on anything like a commercial scale. The following notes summarize the main differences:

1. The low temperature (450–550°C.) of the walls of the oven reduces enormously the rate of transmission of heat through the charge, or, in other words, it reduces the velocity of the zone of fusion. For this reason, a thickness of four to five inches is the maximum that can be treated in stationary charges within economical limits of time.

2. The resistance of the fused zone to the passage of gas is enormously increased as the temperature diminishes. It has been estimated by O. B. Evans (*J. Gas Lighting*, **1913**, 587) that the resistance offered to the passage of gas at 540°C. is about seven times greater than at 700°C. Owing to this extremely high resistance, if for any reason the outer zone becomes choked, the gas accumulates in the charge to such an extent that serious gas pressures are developed. In several cases Evans has found that, when dealing with resinous coals, the gas escapes from the central portion of the charge, not in a direction at right angles to the containing walls, but parallel to them, so that the resulting coke appears as if it were built up of extremely thin layers. This seems to indicate that in low-temperature carbonization, the outer layers are much more resistant to the passage of gas than is the case in high-temperature carbonization.

3. The time during which the coal is in a state of semi-fusion is considerably prolonged.

In the case of high-temperature carbonization, the time-temperature gradient is rather steep, and the interval of time during which the coal is in a state of fusion is comparatively short. In the case of low-temperature carbonization, however, this period is considerably prolonged and owing to this prolongation of the pasty stage, with the high pressures that are induced in the coal mass, the cell cavities in low-temperature coke are considerably larger than is the case with high-temperature coke. This produces ultimately a considerable expansion in the coke, an expansion often great enough in the case of some resinous coals and with well filled retorts to choke up the gas outlet completely. With such coals a considerable space must be left in the retorts to allow room for expansion, and the economic efficiency of the process is thus seriously affected. Further, the coke becomes porous and friable.

4. Any free space left at the top of the coal charge increases the amount of air that is left in contact with the coal. This exerts a most deleterious action when the coal is carbonized at low temperatures and results in the formation of a friable, powdery coke.

It is evident that the low-temperature carbonization of bituminous (coking) coal involves the solution of a number of problems, many of which are of a most conflicting character. The records of the Patent Office contain a number of attempts to solve these problems; and of these, three main classes can be distinguished, *viz.*:

1. The use of externally heated, intermittently charged retorts.
2. The use of intermittently charged retorts, internally heated.
3. Continuous processes in which the coal charge is carried forward by automatic means through a retort which may be heated either externally or internally, or by a combination of both methods.

Externally Heated Retorts.—The various types of "coalite" retorts are on the whole typical examples of low-temperature retorts. Their failure was due to the lack of detailed knowledge regarding the constitution of coal, and also to the difficulty of adapting the system for carbonization on a commercial scale. The coalite trials proved one thing very clearly, however, and that was the necessity of carbonizing the coal in layers as thin as was compatible with commercial requirements. This result is achieved in a very simple manner by the Tozer retort of the

Tarless Fuel Company. In this retort, the coal is charged in concentric layers, so arranged that no layer is more than 4 to 5 in. thick. It is obvious that much larger charges can be got into the same space than in the coalite process, the coal can be charged much more rapidly, labor charges for handling are reduced, and the heating of the retorts can be made very uniform.

The retorts are used in conjunction with Simpson's process for heating coal under a vacuum of from 20 to 26 in. of mercury. The use of such a high degree of exhaustion has certain obvious advantages. The oxygen left in the retort after charging is reduced to a minimum, the liquid and gaseous products would be removed very rapidly from the retort and possibly distillation would be effected more readily. The influence of the vacuum on the quality of the coke produced is not clear. Porter and Taylor state (*Tech. Paper* **140,** *U. S. Bureau of Mines*) that Pittsburgh bituminous coal yielded a light, inferior, porous coke when slowly heated at atmospheric pressure, but at a pressure of less than 30 mm. it produced a dense coke. The reason for this is not very clear, but apparently the use of a vacuum produced a decrease in the tenacity of the tar film.

On the whole, a vacuum process offers certain advantages over those carried on at atmospheric pressure; but, on the other hand, from a commercial standpoint it has certain disadvantages which are obvious to workers familiar with coal carbonization on a large scale.

Taking the Tarless Fuel process as a whole, it is attractive in many respects, but it has yet to prove its capacity for satisfying commercial requirements on a big scale.

A process that has attracted considerable attention is that carried on by the Barnsley Smokeless Fuel Company. This differs in many essential aspects from customary low-temperature practice, and it might perhaps be briefly dealt with. In the first place, the Barnsley retorts are made of fireclay instead of cast iron, the usual material used in low-temperature retorts. Cast iron is certainly not an ideal material; its disadvantages were early recognized by the gas industry and led to its substitution by clay retorts. In the Barnsley plant vertical retorts of rectangular cross-section are used which are somewhat wider than those used in most low temperature processes. In these (Eng. Pat. 108200) four varying zones of heat were maintained, the lowest being at a temperature of about 450°C., the next 500°, the next 550°, etc., while finally, in the free space at the top of the charge, a temperature of 900 to 1,200°C. was maintained. In this space was suspended a grid made of some suitable material (metal, metal oxide, fireclay, or carbon), so that the gaseous compounds of distillation were subjected over as great an area of contact as possible to the temperature necessary to convert the paraffinoid tars to aromatic hydrocarbons.

Internally Heated Retorts.—In this type the coal charge is heated by the actual passage through it of inert gas preheated to a temperature sufficiently high to carbonize the charge. On purely theoretical grounds, this proposal is extremely attractive. The bulk of the time occupied in present systems of carbonization is taken up in heating the innermost layers of the coal, and if these could be heated from the outset considerable economies in time could be effected. A considerable number of attempts have been made to carbonize coal by passing through it a current of inert gas heated to a temperature of from 400 to 600°C., and Parr and Olin (*Univ. of Illinois Bull.* **60**) had some excellent results on a small scale by this method.

As far back as 1890, Parker (Eng. Pat. 67, 1890) proposed to pass steam, water-gas or some other suitable gas, superheated to 500 to 600°C., with a view to making smokeless fuel, and a number of other inventors have followed along similar lines. In the case of bituminous (resinous) coals, the old difficulty arises that, when the coal reaches the pasty stage, it becomes impervious to the passage of the gas, but there seems to be no reason why the method should not be used for shales and cannels, or for coals that are not fusible.

The results obtained by McLaurin with a process of this type (see *J. Soc. Chem. Ind.*, **1917**, 620) are extremely interesting. As would be expected, cannel coal proved to be quite easy to work when carbonized by means of a stream of hot producer gas, but it was also found that Cadder coking coal if screened came out of the retort in the same shape and same size as it was put in. McLaurin suggests that this is due to the slow heating to which the coal was subjected and that under those conditions it did not intumesce. If this condition is applicable to all coals, it opens up possibilities of an extremely interesting character. Evans, however, has not found it possible to repeat this result with the highly resinous coals of South Wales, except under conditions in which oxygen was present in the heating gaseous medium.

The effect of oxygen, when coal is carbonized at low temperatures, has already been discussed, and Evans is inclined to believe that the small quantity of oxygen which would be present in the hot producer gas in McLaurin's experiments played as important a part as the slow heating. A typical analysis of the producer gas gave 0.9 per cent. of oxygen, so that there seems to be every reason for believing that the coal was carbonized in an atmosphere containing a small proportion of this gas, an idea which is confirmed by a study of the properties of the tars obtained.

Another proposal of this type is that given by Lamplough (Eng. Pat. 108343, 1917), the heating medium in this case being steam.

On the whole, internal heating seems to offer considerable possibilities in the treatment of shales, cannels, and possibly certain types of coal if carefully screened; but, as McLaurin and others have found, difficulties would arise in the carbonization of fine coal in this way. There is perhaps one point that would need consideration, and that is, if a small proportion of oxygen were systematically introduced into the heating gas, what would be the effect upon the tars produced? These apparantly would have a similar composition to the old Jameson tars, which were produced under conditions theoretically analogous to those existing in McLaurin's process.

Continuous Processes.—The third class of retort which has been proposed for the low-temperature carbonization of coal is that in which the coal is carried forward through the furnace by means of a conveying system.

The Archimedean screw has been suggested as a suitable carrier for quite a long time. A most interesting anticipation of one of the most modern of these systems is given in Patison's Eng. Pat. 569, 1873, in which coal, shale, or other fuel is carried through a heated retort by means of a worm conveyor. For low temperatures—with a high oil yield—the inventor proposed to use a cast-iron retort, but for high temperatures he suggested the use of a fireclay furnace.

The well-known Del Monte system differs only slightly from this system; but it had one innovation, and that was in the use of a screw mounted on a hollow shaft, which was heated internally by a row of jets from a central gas pipe. Further, the coal was subjected to a fractional distillation, one end of the retort being maintained at a considerably lower temperature than the other. This retort again could be used for wood, shale, lignite, or peat; but with coking coals, the swollen pasty mass which was produced completely prevented the working of the screw.

There seems to be no reason—apart from engineering difficulties—why the coal should not be conveyed through a furnace by some system in which the coal itself is not stirred.

A system of this type that has been worked with some degree of success is that introduced by Pringle and Richards. In this the coal is carried by means of an endless conveyor through a retort, the temperature of which is maintained at about 500°C. The conveyor itself is fitted with compartments so as to subdivide the coal into a number of separate small charges, each of which is rapidly heated to the desired temperature. The coal itself is undisturbed in its passage through the retort and leaves as a porous semi-coke which is an excellent domestic fuel. This process as yet has only been worked on an experimental scale; the obvious difficulties are of an engineering character and whether or not they can be overcome on a large scale plant remains to be proved.

Present Status of European Processes.—Since Evans published the foregoing summary, the coalite, Barnsley and one or two other processes have been taken over by a recently organized company, operating under the title of "Low-temperature Carbonization Limited," and development work is being continued. Other processes undergoing development are the "Tarless Fuel," "Marshall and Tozer" and the "Summer's Coke Oven," in England, and the Del Monte process in Spain.

In the Summer's process, granulated coal is fed continuously onto one end of a long horizontal plate which extends through the length of the oven. This plate is given a shaking motion which keeps the coal agitated and advances it slowly through the oven in a thin layer.

CONSTITUTION OF COAL

The phenomena of the distillation of coal at low temperature are intimately bound up with the constitution of the coal that is treated. Hence, a clear understanding of the nature of the coal itself is a necessary prerequisite to a study of the subject. E. C. Evans* gives a brief summary of the subject, and the more

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* *Loc. cit.* on p. 395.

recent studies of Bone, in England, and of Thiessen, in America, are reviewed below.

The Chemistry of Coal* by William A. Bone.

"*The Coal Substance.*—Chemically speaking, coal is an exceedingly complex substance, and the investigation of its real composition and constitution is beset with extraordinary difficulties. Years ago, before I took up special research work upon the constitution of the coal substance, I thought I knew at least something about it; but the chief outcome of some years of sustained experimental inquiry into the matter has been to convince me of my desperate ignorance of it, and of the total inadequacy (in some cases even *fallacy*) of most of our current conceptions concerning it. The further I go the less do I seem to know about it; but I have accumulated a mass of well-ascertained facts which do not at all fit in with the commonly accepted theories. Doubtless my experience is borne out by that of other investigators; indeed, I can hardly imagine any chemist with the name claiming that he has as yet touched more than the mere fringe of the problem.

"At present we can say very little more than that the 'coal substance' (*i.e.*, the *organic* part of coal, excluding all adventitious mineral matter) is essentially a mixture, in variable proportions, of the degradation or transformation products of the ligno-celluloses, proteids, and resinous matters comprising the vegetable *débris* from which it originated. The chief problem which confronts the chemist is (*a*) to devise means of discriminating between these several products in the coal substance, (*b*) to find out how far each has been changed in the long transformation process, and (*c*) to determine how each is likely to affect the properties and uses of the coal, especially how each class behaves after the coal is subjected to destructive distillation. Indeed, as I have already said in my book upon 'Coal and Its Scientific Uses' (Longmans, Green & Co., 1918), 'our chemical knowledge of coal must be considered deficient until we are able, not only to give a rational analysis of any particular coal, but also to predict the influence of each type of constituent upon the behavior of coal at all temperatures and upon the yields of the various products obtainable when it is distilled at any given temperature.'

"**Origin of Coal.**—The vegetable *débris* from whence coal originated countless ages ago in all probability was chiefly composed of the following three types of substances, namely:

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* Condensed from *Combustion*, October, **1920**, 26.

"(*a*) *Ligno-celluloses*, essentially carbohydrates [$(C_{12}H_{18}O_9)_n$] of a 'cyclic' constitution;

"(*b*) *Resinic bodies, i.e.*, gums, resins, and waxes, all of them compounds of carbon, hydrogen, and oxygen only;

"(*c*) *Proteid bodies, i.e.*, compounds of carbon, hydrogen, oxygen, nitrogen, and sulphur.

"During the transformation process into coal, these have been subjected firstly to the disintegrating influence of decay (*e.g.*, as in modern peat bogs) and *afterward* to the combined action, through long ages of great pressure and a slowly rising temperature (up to, but probably not exceeding, 300°C.) as the incipient coal fields were subsequently overlaid and 'blanketed' by accumulating newer *strata*. During such transformation it is probable that the less stable ligno-celluloses and proteid constituents would be more changed than the resinic bodies.

"There is now a considerable body of evidence proving that the ligno-celluloses have undergone a change involving '*internal condensations*,' with loss of carbon dioxide and steam, without, however, destroying the fundamental cyclic character of their chemical constitution. The retention of this cyclic character explains many undisputed facts about the behavior of bituminous coals on carbonization, and especially the production at low temperatures of 'hydrobenzenoid' types and at high temperatures of benzols ('aromatics'). Certainly, according to my own researches, not only is the chief part of the 'coal substance' composed of the transformation products of the ligno-celluloses, but also the characteristic differences between brown coals (lignites) and those of the bituminous class are mainly due to the said transformation process having, in the last named, proceeded much further. Indeed, as I have recently discovered, brown coals and lignites may easily be transformed, by suitable physical treatment, into something very like black coals. Details of these experiments will shortly be published.

"**Coking not Caused by Resins.**—The 'resinic' constituents of bituminous coals, though important, probably do not determine, except in a subordinate degree, their properties and behavior on distillation. At one time it was commonly thought that the coking properties of coals are chiefly determined by the resinic bodies; but recent experiments in my laboratory have thrown considerable doubt upon this view, if they have not altogether disproved it. Precisely how and when it arose in the first instance, I do not know, but it rests on a good many experiments of doubtful validity, and is backed by much loose reasoning. I am inclined to think that the resinic constituents of a bituminous coal play a relatively subordinate *rôle* in determining its coking properties, and I hope shortly to publish conclusive experimental evidence in support of my contention. Seeing that we are only just beginning to understand the matter, dogmatic statements concerning it are to be deprecated and are entirely out of place in scientific literature. During the course of our researches, a method of separating the resinic constituents of coal and isolating them in a pure condition has been devised and worked out; we are now engaged upon the much harder task of investigating whether or not (and if so, then to what extent) they differ in different types of coal.

"The nitrogenous constituents of the coal substance, from whence the world derives so much of its ammonia requirements, are probably the transformation products of the proteids of the original vegetable *debris.* As yet chemists have not been able to devise methods for separating them from the cellulosic constituents, and we know very little, indeed, about either their constitution or their modes of decomposition. All this is still, comparatively speaking, an unexplored region."

Physical Structure of Coal.—White and Thiessen have reviewed the origin and constitution of coal in *Bulletin* 38 of the U. S. Bureau of Mines (1914), and the following paragraphs, together with those on the history of coal research, form an abstract of parts of a recent paper by Thiessen.*

The most conspicuous constituents are the alternate strata of bright coal, known as "anthraxylon," and of dull coal. The latter, under the microscope, is seen to be composed of alternate striations of black and lighter colored constituents, the black being called "anthraxylon" (meaning wood coal) and the lighter portions "attritus." Bright coals are much more readily coked than dull coals taken from the same seam.

The anthraxylon was formed, largely, from the remains of the stems, roots, leaves and bark of the plants which grew in the ancient peat bogs, while the attritus contains various plant debris often including cuticular material and spore-exines.

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* "Recent Developments in the Microscopic Study of Coal," by R. THIESSEN; read at meeting of the Coal Mining Institute of America, Dec 9, 1920, Pittsburgh, Pa. (*Coal Age*, Dec. 9, 1920, to Jan. 6, 1921.)

These are the hard shells or spore cases which have resisted disintegration, although, in some coals, they have been flattened by pressure. The spores often contained vegetable oils, which have become mineralized and form part of the resinous matter in the coal.

Coal also contains vertical cracks filled with quartz deposited by water which has infiltrated from the rocks. Most of the pyrite is of similar origin and occurs largely in small crystals (many of microscopic size), scattered through the bright coal. Apart from intrusive quartz and pyrite, the bright coal is much purer than the dull coal, which contains by far the greater part of the ash. Since the latter often forms only a small part of the coal, it may be separated by suitable cleaning processes (page 608).

History of Coal Research.—The theory that coal was formed from ancient peat deposits was first advanced by Beroldingen in 1778 and 1792, but this theory was not generally accepted until after it had been revived by McCulloch in 1831. Further advances in the study of the formation and structure of coal were hindered by diverse theories until the microscope had been sufficiently developed to form the true basis for the study of peat and coal as well as living and fossil plants. Moreover, it was not until the present century that it was possible to correlate the various sciences bearing upon the subject.

In recent years most of the investigations of coal have been made by botanists with a purely botanical point of view. Much credit for the resumption of this line of attack must be given to David White of the Geological Survey. White saw that, in order to get a proper understanding of the nature of coal, it must be attacked from the botanical side first and from the chemical side later; also that its study must begin with the peats, and continue successively on through the lignites and the subbituminous coals to the bituminous coals.

Before actual microscopic examination of coal could begin, difficulties in preparing it for examination had to be overcome. These in themselves constituted no small problem. Furthermore, before the nature of coal could be satisfactorily investigated, all information relative to the subject in other allied branches of science, such as geology, botany, chemistry, colloid chemistry, physiography and fossil botany, had to be collected and brought into harmony.

The progressive ageing of coal, from peat to lignite and bituminous coal, is accompanied by the loss of oxygen, hydrogen and carbon, but the deoxygenation takes place at a more rapid rate than the elimination of the other elements. Hence the lower oxygen content of the coals of higher rank, and it is only high rank coals that are readily coked by the usual methods.

The following literature should also be consulted by those interested in the constitution of coal:

Publications of the U. S. Bureau of Mines, *Bull.* **29**, "The Effect of Oxygen in Coal," by DAVID WHITE; *Bull.* **38**, "The Origin of Coal," by D. WHITE and R. THIESSEN, 1913; *Bull.* **117**, "Structure in Paleozoic Coals," by R. THIESSEN, 1920; Also, Monograph on the "Constitution of Coal," by M. C. STOPES and R. V. WHEELER, London, 1918. Published for the Dep't. of Scientific and Industrial Research by His Majesty's Stationery Office. This is based on a paper read before the London section of the Society of Chemical Industry, and contains a very comprehensive review of this interesting subject.

THE RESEARCHES OF PARR

The pioneer research work in America, in connection with the distillation of coal at low temperature, was done by S. W. Parr, Professor of Applied Chemistry in the University of Illinois, and his collaborators. They have been published by the Experiment Station of the University of Illinois in its *Bulletins* No. **60** (1912) and No. **74** (1915), from which the following extracts are taken.

Historical.*—Researches in the low-temperature distillation of bituminous coals have been carried on at the University of Illinois since 1902. In a series of preliminary experiments, on heating coal to temperatures ranging from 250 to 500°C. for periods of less than an hour, it was found that the percentage of fixed carbon was increased by more than 25 per cent. and that there was a corresponding decrease in volatile matter to a point where the formation of smoke was prevented altogether.

In order to eliminate as far as possible those variables which would result from oxidation, Parr and Francis in continuing this work heated Illinois coals in non-oxidizing atmospheres. Choosing nitrogen first as the most suitable medium for this purpose, a careful study was made of the quantity and composition of the gases and heavy residues produced at different tempera-

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* *Univ. of Ill. Bull.* **60**, 1912; and *Bull.* **79**, 1915.

tures below 400°C. With a view to securing an absolutely inert atmosphere, after finding that the ordinary commercial nitrogen was contaminated with oxygen, the air in the retort was displaced by steam.

The coals heated in these media underwent changes which rendered them smokeless in ordinary combustion. However, on account of the rotary motion given the retort in order to equalize the temperatures, the coke product came out in a loose granular state much like that of the original coal.

Oxygen Removed.—As has already been stated, the decompositions occurring at temperatures in the neighborhood of 400°C. include the liberation of oxygen, or, as it is frequently designated, the water of constitution. Since this ingredient of the raw coal is non-combustible, it has the same function as so much ash. Its removal, therefore, serves to make of the resulting material a richer or more concentrated fuel. This feature is still further promoted by the removal of the hygroscopic or free moisture which usually exceeds in amount the water of composition. This point may be illustrated by the accompanying table, wherein the heat values per pound of the original coal are compared with the heat values per pound of the residual coke. There is also given an estimate of the amount of non-combustible material removed in the form of water in the process of decomposition.

TABLE XLIV

Samples	B.t.u. per pound as received	B.t.u. per pound after treatment	Gain, thermal units	Gain, per cent.	Estimated loss of total non-combustible free and combined moisture
Williamson Co.	12,695	13,150	455	3.60	10.30
Saline Co.	13,583	13,746	163	1.63	8.93
Vermillion Co.	12,673	12,892	219	1.72	13.30

Porter and Ovitz[*] made an extended study of the volatile matter of coal with a view to determining the influence of the gas composition factor on the efficiency in the use of coal in various industrial processes with special reference to gas producer, coke oven and gas retort operation.

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[*] "The Volatile Matter of Coal," *U. S. Bureau of Mines, Bull.* 1, 1910.

Their investigations show that the composition of the volatile matter of a coal depends largely upon the character of the coal itself. The gases from the younger coals of the West compared with those from the coals of the Appalachian region have high percentages of carbon dioxide and carbon monoxide. Because of the readiness with which these gases are given off, even at comparatively low temperatures (300 to 500°), the writers conclude that these western coals contain compounds having a direct carbon linkage, such as the complex alcohols, aldehydes and acids. They show, further, that, contrary to the theory of Dulong, who assumed that in combustion all the oxygen of a coal combined with hydrogen, in the case of certain low grade highly oxygenated coals nearly two-thirds of the oxygen appears in the volatile products in union with carbon, and that this fact accounts for the discrepancy between the determined heat value and that calculated by Dulong's method.

Higher hydrocarbons, such as ethane, are produced in greatest abundance from the eastern coals and the gas evolved from any coal, subjected to moderate heat only, is rich in the higher paraffins, such as ethane and propane. In the case of Connellsville coal, at furnace temperatures of 500 and 600°C. these higher hydrocarbons constitute about 50 per cent. of the total paraffin content. At about 800°C. the percentage reaches a maximum, when it rapidly falls on account of decomposition by heat.

Burgess and Wheeler,* working on the problem of the prevention of mine dust explosions, and recognizing the relationship that exists between the character of the volatile matter escaping from a heated coal, and its degree of inflammability, studied the composition of the gases evolved at different temperatures.

They found that with all coals, whether bituminous, semibituminous, or anthracite, there was a well-defined decomposition point at a temperature between 700 and 800°C. which corresponded to a marked increase in the quantity of hydrogen evolved. This increase they attribute to the thermal decomposition of one or more of the higher homologues of methane yielding hydrogen and carbon. Ethane, propane, butane, and, probably, higher members of the paraffin series, form a large percentage of the gases given off at temperatures below 450°C.; above 700°, they no longer appear.

* *J. Chem. Soc.*, **97**, 1917.

They believe that the smoke-producing elements consist almost entirely of the higher paraffins, and differ from Porter and Ovitz in excluding ethylene and the related unsaturated gases from this class. This view is based upon experiments made showing that ethylene decomposing at 600°C. deposited very little carbon.

A typical analysis of the gases obtained is given below.

TABLE XLV.—GAS FROM COAL FROM ABERTILLERY, SOUTH WALES (BITUMINOUS)

Temperature	Illumination (C_2H_4, etc.)	CO_2	CO	H_2	CH_4	C_2H_6
500°	5.8	3.9	4.7	8.0	64.5	11.0
600°	4.9	3.2	6.4	25.0	47 2	12.4
700°	2.8	3.4	7.4	34.7	46.2	4.2
800°	2.8	2.5	9.8	50.8	28.6	4.7
1,100°	4.2	1.4	13.0	60.7	18.8	1.8

In a second paper they discuss the results obtained by subjecting coals to a series of fractional distillations in a vacuum and determining the compositions of the gases evolved within well defined limits of temperature. They succeeded by prolonged exhaustion at a low temperature, in removing entirely the paraffin-yielding constituents and leaving behind a compound which decomposed at a comparatively high temperature, yielding only hydrogen.

An interesting table showing the effect of change of temperature on the yield of gas and tar is given by V. B. Lewes.*

TABLE XLVI.—VARIATION OF GAS AND TAR YIELD WITH TEMPERATURE RANGE

Temperature, degrees Centigrade	Gas yield per ton, cubic feet	Tar, gallons	Specific gravity of tar
900	11,000	9	1.200
800	10,000	12	1.170
700	9,000	15	1.140
600	7,750	18	1.115
500	6,400	21	1.087
400	5,000	23	1.060

J. Gas Light., **101,** 823.

Lewes points out that tars produced at temperatures between 400°C. and 500°C. contain relatively low percentages of aromatic substances and high percentages of the paraffin series which are adapted to use as motor fuels. The middle oils are free from naphthalene and yield excellent enriching oils. The pitch having practically no free carbon, he says, forms an ideal electric insulating material.

Variations in the quality and composition of the gas are shown in the following table.

TABLE XLVII.—COMPOSITION OF GASES PRODUCED AT DIFFERENT TEMPERATURES

	400°	500°	600°	700°	800°	900°
Hydrogen	21.2	28.3	33.8	41.6	48.2	54.5
Saturated hydrocarbons	60.1	56.2	30.7	45.0	39.1	34.2
Unsaturated hydrocarbons	6.3	5.8	5.0	4.4	3.8	3.5

The gas produced at the lowest temperatures quoted has a calorific value of 750 B.t.u. and measures 20 candlepower.

THE EXPERIMENTS OF PARR AND OLIN*

This report covers a series of studies made during the period from 1911 to 1913 on the coking properties of Illinois coal. It is a continuation of the work described in *Bulletin* No. **60** of the University of Illinois Engineering Experiment Station.† Its distinctive feature has been the use of an apparatus which would yield the main products of coke, gas, and tar in quantities sufficient for a detailed study of these products, and, to a certain extent, quantities sufficient for a determination of their values by practical tests on a commercial scale.

Resumé of Previous Work.—In the experiments described in *Bulletin* No. **60** the apparatus used had a capacity of 6 to 8 lb. of coal at a charge. Notwithstanding this limited capacity, certain fundamental facts were developed as follows:

(*a*) The formation of coke depends upon the presence of certain constituents having a melting point which is lower than the temperature at which decomposition or carbonization takes place.

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* Extracts from *Univ. of Ill. Bull.* **79**, "The Coking of Coal at Low Temperatures with Special Reference to the Properties and Composition of the Products," 1915.

† "The Coking of Coal at Low Temperatures," by S. W. Parr and H. L. Olin.

(*b*) Oxidation of these compounds may easily take place and the greatest coking effect is obtained where the opportunity for the minimum amount of oxidation has occurred. The condition prescribed, therefore, is that there shall be the least possible exposure to oxidation either before or during the process of carbonization.

(*c*) Coals containing an excessive quantity of the coking substance produce a light porous coke. The texture of the product may be modified by use of pressure and by close packing of the charge and especially by mixing with material which has already passed through the coking process. Such a mixture provides the physical conditions whereby the gases formed may readily pass out of the mass without carrying along the cementing substances.

(*d*) By use of temperatures between 400 and 500°C. all the resulting products are of a type distinctly different from those obtained by the usual high temperature procedure.

Outline of Investigation.—An apparatus was designed to utilize about 100 lb. of coal. Experience in the use of the apparatus indicated also the main principles which should be embodied in a commercial equipment. The coking process was studied, and the mixture for producing the best product determined. It was found that a smokeless fuel may be produced especially well adapted to domestic purposes, including its use in open grates. Its freedom from tar or condensable hydrocarbons makes it easily adapted to generating producer gas, thus affording a good substitute for anthracite coal in suction gas producer practice.

In the study of the composition and properties of the tar, this material was found to have a very low content of free carbon, a relatively high percentage of light boiling distillate, and an unusually high content of tar acids or phenols. The latter fact is of special interest to the wood-preserving industry.

Description of Coking Oven.—The apparatus used in the experiments was an elaboration of that employed in 1910 and capable of producing material in greater quantities.

As shown in Fig. 87, it consists of a boiler-plate shell *A*, lined with asbestos to prevent excessive radiation of heat; within this, forming the coking chamber, was a shell *B* of the same material, containing a cone of light sheet iron *C*, perforated with $\frac{3}{16}$-in. holes, designed to confine the coal charge and to allow a free circulation of gases. To obtain the non-oxidizing atmosphere, such as was used with the old apparatus, steam was admitted from the high-pressure main at *E*, passed through the coil *F*, where it was superheated by the hot currents ascending from the gas burner, and then conducted into the coking chamber. The heat was supplied by a blast ring-burner *D*, connected with the gas and air mains, and no difficulty was experienced in producing the desired temperatures. The charge of crushed coal was fed into the hopper *G* and admitted to the retort through a large gate valve. The coked residue was removed, after cooling the apparatus, through the bottom at *H*. Gases of combustion escaped through the opening *J*, which was connected with a flue, while the distillates were conducted through an outlet pipe to a condenser consisting of several 4-ft. lengths of 1-in. pipe connected by return elbows. Cold water was allowed to drip over this gridiron-like contrivance. The tars were passed through a water-sealed exit at the bottom, while the gases, fairly clean, were collected in a gasometer.

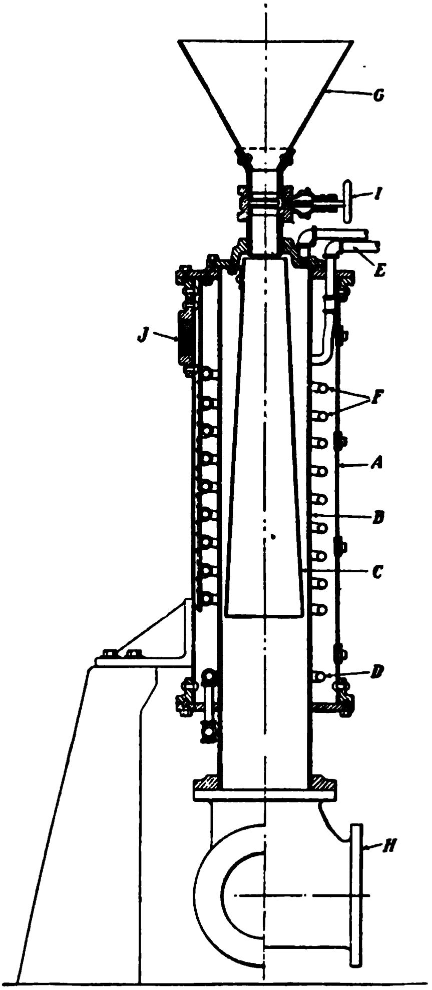

FIG. 87.—Cross-section of apparatus for the low-temperature distillation of coal.

Coking Tests.—To study further the coking qualities of Illinois coals at temperatures ranging from 400 to 500°C., and to obtain a quantity of the coke residue sufficient in amount for practical tests in order to determine its commercial value, a series of runs was made using the apparatus described. Numerous coals from the different fields of the State were included in this set of experiments. Of particular interest during the process of distillation was the behavior of the coals from the northern districts, especially those from Vermilion County. As the heating progressed, a black pitchy substance dripped from the joints of the containing ovens, but it hardened immediately on cooling, forming a brittle mass much resembling asphalt. This was undoubtedly the cementing principle which is instrumental in forming coke. According to Lewes, it consists of substances derived from the resins of the original coal sources, which melt at about 300°C. and decompose at slightly higher temperatures, yielding on the one hand liquid products which distil out as tar vapors and hydrocarbon gases, and, on the other, a pitch residuum, which at 500°C. forms a mass of coke. His general theory that these resinic substances are readily oxidizable and in their oxidized condition have much to do with coke formation is borne out in these experiments by the fact that no weathered coal of any type produced the gummy exudation mentioned, although there was no apparent diminution in the amount of gases given off. Compared with the bituminous coals of the Eastern States, those of Illinois are exceedingly rich in this resinous binding material. Even those from the southern districts of the State, while not as "fat" as those from Sangamon and Vermilion counties, nevertheless much surpass in this respect coals like the Pocahontas, and those from Ohio and Pennsylvania. Strangely enough the abundance of the coking material which the western types possess is the cause of their inferiority in the matter of making dense, hard coke; for, with the decomposition of the resinic bodies and the deposition of cementing carbon, there occurs at the same time an evolution of large quantities of gases which inflate the pasty mass and make the resulting coke more or less light and spongy. Indeed, certain Vermilion County coals, after being heated under conditions which allow free expansion, present the appearance of hardened froth, because of the excessive development of cell structure in the coke.

The porosity of the product may be appreciably reduced by subjecting the contents of the oven during the heating period to a considerable pressure. Another means to the same end, which was recognized in the first experiments and which has been applied in the later series, is the addition of inert coke dust to the raw coal as fed into the retort. This material, acting in the capacity of a "blotter," reduces the plasticity of the softened mass and allows the gases to escape freely without producing a blowing effect. The diluting medium was a mixture of various semicokes which had accumulated in the course of the work. The material was crushed and ground to a fineness of 40 or 50 mesh and thoroughly mixed with the rest of the charge in ball mills.

Adaptation of the Coke to Domestic Appliances.—A limited amount of the coke was available for testing its adaptability to house-heating purposes. The ordinary household appliance is especially well adapted for distilling off the hydrocarbons of coal and sending them into the air unburned or partly burned and accompanied by large volumes of smoke.

In the coke product here described the heavy hydrocarbons have been removed. The coke itself, therefore, is clean both in handling and in burning. However, there remains approximately 20 per cent. of volatile matter which enters into the process of combustion after the coke has attained a temperature at or beyond the point to which it had been subjected in the coking process. These conditions result in a free-burning substance yet one whose combustible constituents may not produce smoke in burning.

An open grate was selected as furnishing the best opportunity for observing the behavior of the material. The results are summed up as follows: the coke ignites readily, it retains its shape through the process of combustion, a bed of glowing coals quickly results, the very indifferent provision for draft as found in an open grate is sufficient for keeping the combustion lively, there is no smoke produced, and fire is retained over a long period of time, because the interior of the larger pieces holds the fire and continues the combustion until all the carbonaceous matter is consumed. While the temperature commonly attained by a grate fire would not furnish positive evidence as to the formation of clinker, the indications so far as they went were altogether favorable. A small amount of coke was tested by burning in a hot-air furnace. Not enough material was at hand for a complete test; but so far as observations could be made, it was as favorable as the test in the open grate.

SUMMARY

1. Coke of good density and hardness may be made by mixtures of semi-coke and raw coal if both are finely divided and

evenly mixed. A variation is noticeable in the quantity of such non-coking material which may be incorporated with different coals. For example, fresh coal from Vermilion County will carry such an addition of 100 per cent. of its weight to advantage. Coals from Saline and Williamson Counties give coke of the highest density when mixed in the proportion of 50 per cent of their weight with semi-coke.

2. The coke resulting from the low-temperature process has from 18 to 22 per cent of volatile matter remaining; but since it has been heated above 400°, there should be none of the tar constituents remaining. The most convincing test on this point as also the method of arriving at a conclusion as to its adaptability for such work, was to try out the material in a suction gas producer. The results indicated that no clogging effect whatever results, thus showing the absence of tar bodies. The physical operation of the producer as well as the grade of the gas produced was fully equal, if not superior, to the performance of the outfit when anthracite was used.

3. The semi-coke has such an amount of volatile matter remaining, together with the right degree of coherence, as to make it especially well adapted to household use. It is clean to handle, free from dust, and burns without smoke or the formation of soot. Especially to be noted in this connection is its ability to retain a fire without undue attention as to drafts, etc.

4. The average specific gravity of the tar is 1.069. It is rich in low-boiling distillate passing over at 210°. This product averages 18 per cent of the total. The pitch residue amounts to approximately 30 per cent and is remarkably free from precipitated carbon.

5. The adaptability of the tar for wood preservation processes seems to be indicated by the high percentage of tar acids. These constituents make up from 28 to 30 per cent of the crude material. The larger part, about 22 per cent, is found in the second distillate (210 to 325°), only about 7 per cent coming over below 210°.

6. Approximately 10 per cent of the crude tar is found to be low-boiling distillate free from the tar acids and suitable for use in internal-combustion engines.

7. Naphthalene is absent. The free carbon in the crude tar is less than 2 per cent and the residual product, after the light distillate and heavy oils are removed, would be classed as hard pitch.

LOW-TEMPERATURE CARBONIZATION AND ITS APPLICATION TO HIGH-OXYGEN COALS*

By S. W. Parr and T. E. Layng

University of Illinois, Urbana, Illinois

The low-temperature carbonization of coal is ordinarily understood to mean its destructive distillation at temperatures not in excess of 750 or 800°C.

Comparisons with High-temperature Carbonization.—Certain features which accompany this particular condition may be briefly enumerated as follows:

The demarkation of temperatures indicated by 750 to 800°C. is not arbitrarily chosen, but seems to be a natural dividing line between the decomposition processes which liberate heavy products which are largely condensable and those reactions which deliver light or non-condensable compounds. Another method of stating the case would be to say that below 750° the volatile products are tars or oils and some fixed gases, while above 750° the volatile products are gases only.

Again, under low-temperature conditions the volatile constituents are largely the initial products of decomposition, as set free by the various components of the coal, and in the main they are not subject to any great modification by secondary processes of decomposition. By this it is not intended to affirm that no secondary reactions occur. By their very nature, these volatile products are susceptible to change, but these changes are more in the nature of interactions or reactions among themselves or with the decomposing constituents; whereas, under high-temperature conditions, there proceeds a very positive breaking down of these easily decomposable compounds. In other words, the high-temperature process accentuates the matter of secondary decomposition so that the ultimate products bear little relation to the character of the substances that first result from the destructive distillation of the coal.

Yields.—This contrast in products leads to the next statement as to yields. A bituminous coal, which under the ordinary high-temperature process yields 10 gal. per ton of condensable material, will, where these secondary decompositions are lacking, yield from 20 to 25 gal. per ton. Indeed, certain types of coal have been found where the condensable products are in excess of 30 gal. per ton.

Character of Low-temperature Products.—Other interesting features relate to the character of the compounds that are discharged under the low-temperature range. No information along this line can be gained from a study of high-temperature products, because their character has been quite altered or obscured by the secondary decomposition resulting from the passage of the initial volatile constituents over or through the

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* *J. Ind. Eng. Chem.*, **12** (1921), No. 1, 14.

highly heated passageways or masses of coke. As a matter of fact, it is only by a study of the products as they are discharged at successive temperature stages that we can arrive at any safe conclusions as to the character of the initial products of decomposition. It will not be strange, therefore, if we have to modify to a considerable extent our present conception of the decomposition procedure.

Briefly stated, we shall find the order to be: water, carbon dioxide, and methane, with respective temperature ranges of approximately 250 to 300°, 300 to 350°, and 350 to 400°C. At the latter stage, there begins also the discharge of ethane and heavier hydrocarbons, with the beginning also of condensable products in which the sulphur and oxygen compounds predominate. The latter show themselves in the form of tar acids. The chief feature concerning the sulphur is that the part which is in organic combination in the coal is quickly discharged. A range of temperature, however, seems to be attained where there is substantially no sulphur decomposition, as shown by an almost total absence of this constituent in the gases. However, at higher temperatures where decomposition of the iron pyrites occurs, the volatile sulphur compounds appear, largely in combination with the tar or oil constituents.

This substantial absence of secondary decomposition accounts for a number of characteristic variations in the by-products. For example, the tars are thin and light, having a consistency much more resembling oils. They have a specific gravity so nearly approaching unity that the separation of water from the oil is difficult. The tars contain practically no free carbon. The gas yield per pound is less, being from 60 to 80 per cent. of the volume obtained by high-temperature processes, and both gas and tar are free from naphthalene.

These differences are such as one would naturally expect as a result of the presence or absence of secondary decompositions. The argument in favor of the tars is that, in addition to their much higher yield, it would be better to carry out the possible decompositions upon them as a distinct process under exact control and for the production of specific substances, rather than to submit them to the more or less uncertain and haphazard reactions which result from the high-temperature decompositions.

Another method of stating the important feature of oil or tar yield is from the viewpoint of our rapidly vanishing petroleum supplies. If, for example, a Scotch shale with a yield of 20 or 25 gal. of oil per ton and no by-products of value is a workable proposition, why may we not look with favor upon a bituminous coal having a potential yield of liquid fuel of 20 or 30 gal. per ton and a by-product in the way of a smokeless solid fuel of even greater value than the oil?

Coking of High-oxygen Coals.—Since the most of our high-volatile coals are, as a matter of fact, also high-oxygen coals, the question at once arises as to the possibility of producing a marketable coke from high-oxygen coals. Concerning the coking of such coals, we shall doubtless be obliged to recast to a certain extent our theories concerning the chemistry of coal carbonization.

Theoretical Considerations.—In a general way, it has been held that a coal with an oxygen content above a certain amount, for example, an oxygen-hydrogen ratio much in excess of 50—50, or, say, 6 per cent of oxygen to 5 per cent of hydrogen, should be classed as a non-coking coal. This would seem a harsh decree for Illinois coals, which exceed this oxygen ratio by almost 50 per cent.; especially since the reserve tonnage of such coals within the boundary of Illinois exceeds the reserve tonnage of any other state in the Union, Pennsylvania and West Virginia not excepted. Now the fact that a low-oxygen content is characteristic of the coals which make good coke by methods now in use may be a coincidence and not a cause. At least, there has never been any very good explanation of why a high-oxygen content should result in poor coke. We are positive in this connection only of one thing, namely, that we have found no explanation which we can guarantee as satisfactory in all cases, or in all respects. But experiments have proceeded to a point where a few fundamental propositions are seemingly established. For example, that part of the coal which is "phenol-soluble"* has a definite melting point, and this material in its final decomposition furnishes the binder for the production of coke. It is largely composed, however, of highly unsaturated compounds, and these, if allowed to come in contact with certain decomposition products of the fully-oxygenated type, unite with the same to form compounds having totally different characteristics, chief among which is the absence of any melting point, and consequently the absence of the coking property.

Let us go a step further in this illustration. A coal which is finely divided and which has been exposed to the air for some time will have lost its coking property, even though the coal be of the so-called coking type. Now, if our reasoning is correct, such a coal might be so handled in the coking process as to eliminate those oxygen compounds in such a manner as to avoid the disastrous reactions with the active coking constituents. Experimental evidence is in hand showing this can be done. The same reasoning, of course, will and does hold true for the coals with a high normal-oxygen content. They may be dealt with in such a manner as to produce a very weak and indifferent coke, as seen in the ordinary gashouse product; or under other conditions where deleterious interactions are avoided, a coke of altogether different texture and density may be the result.

Further, these considerations are not inconsistent with the theo-

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* PARR and OLIN, *Univ. of Ill. Eng. Exp. Sta., Bull.* 60.

ries now being developed by Thiessen as to the composition of coal. He seems to show that the phenol-soluble portion is the degradation product, through geological processes, of cellulosic material; and not, as Lewes would have us believe, of resinic bodies. From this standpoint, we should say, then, that this material which constitutes the true coking substance has a marked tendency towards a reversion of type. This may show itself either in the interaction which occurs during the destructive distillation process or more readily in the effect of weathering. A striking illustration of the effect of weathering is occasionally found in the case of Illinois coals, where the outcrop shows a marked reversion of type to the extent that it has every characteristic of a lignite, whereas the coal from the working face, completely removed from weathering effects, shows no such reversion.

Temperature Control.—Thus far this discussion has dealt only with some of the theories underlying the carbonization of high-oxygen coals. The methods which suggest themselves for securing the conditions indicated involve a procedure whereby the changes may be brought about in stages or what may fairly well be designated as fractional decompositions. Such a method implies an observance of temperature control, quite unknown and quite impossible under the ordinary high-temperature conditions. This matter of temperature control involves the entire question of successfully carrying out any sort of a low-temperature program. Indeed, it is of such paramount importance, and in all of its bearings upon the situation involves so many factors, that its proper discussion should be reserved for a separate consideration. However, brief reference is made here for the purpose of indicating that the preceding discussion is not purely academic and theoretical, with no hope of possible attainment in practice, but, as a matter of fact, may be found the most logical procedure even under industrial conditions.

The first question we meet is this: Can we carry heat to the center of a non-conducting mass by conductivity methods alone, without doing violence to all ideas of temperature control? If we look to the modern by-product oven for an answer, we shall be obliged to say at once, "No." In this practice, for the temperature at the center of a coal mass of 18-in. cross-section to reach the beginning of the carbonization stage requires at least 14 out of the total of 18 hr.; and even this is accomplished only by maintaining a surrounding temperature of 1,000° as an impelling force against the nonconductivity conditions prevailing. Obviously, the low temperature idea in any of its bearings is incompatible with such procedure.

A number of methods have been proposed for meeting this condition of nonconductivity without the use of excessive temperature. The most frequent is the application of temperatures within the prescribed limit to a mass of coal so narrow in its cross-section that the penetration of heat from the two sides would be sufficiently uniform and rapid to meet the requirements so far as ultimate temperature throughout the mass is concerned. The same idea is involved in any briquetting process with subsequent application of heat to the briquets, the factor involved being the cross-section of the individual briquet masses.

In the process as we have been developing it, utilization has been made of the ability of the coal under proper conditions to supply its own heat, which may thus be made to proceed autogenously throughout the mass without reference to its size or cross-section, and without the application of any external heat in excess of the prescribed maximum for the theoretical conditions involved in the low temperature idea. Fortunately these reactions which are responsible for what is well recognized as the exothermic behavior of coal in the process of carbonization occur well within the prescribed limits. As a matter of fact, they are most in evidence at temperatures of approximately 300 to 400°. Up to date the experiments have not involved cross-sections of coal greater than 16 in.

Character of Coke Obtained.—The appearance of the material produced under these conditions is strikingly characteristic. It is uniform in texture, without any zoning evidence of progressive stages in heat transmission, dense, and of good strength, and without any of the fingering effect characteristic of the high temperature method. The volatile matter retained under these conditions may vary from 5 to 15 per cent, depending on the coal and the ultimate temperature attained. It contains no condensable hydrocarbons, and if discharged by application of further heat would appear almost entirely as hydrogen and methane. As would naturally be expected where an autogenous generation of heat is involved, the time element for bringing about the carbonization is greatly reduced, the average time being from 3 to 4 hr. Experiments involving the exact measurement of the amount of heat available from different coals, the conditions for its greatest development, and the limits as to mass wherein it may be made practically operative, are still matters of experimental research.

Method of Retorting.—The process is essentially a discontinuous one, as is the case with the ordinary coking process. At each of the different stages it is necessary to observe rather exacting conditions and, when the reactions are completed, discharge the batch and begin on a new one. The amount of heat involved in the exothermic reactions is being investigated. It is evident that it is not enough to do all the work involved in the vaporization of the water, the heating of the coal, the volatilization and heating of the escaping products, and supplying the radiation loss.

Ammonia Yield.*—The actual nitrogen in combination as ammonia is

* Extracts from the discussion on the paper. (From Parr's replies to questions.)

very nearly the same in amount as is produced from the high-temperature process, but it is not due to similar conditions. In the high-temperature process a large part of the ammonia is dissociated and the yield represents the residue. In this process, the ammonia is not decomposed to the same extent. In addition to the nitrogen recovered as NH_3, there are also some ammonia compounds in the tars, such as amines. Still more is found in the coke.

Nitrogen, sulphur, and probably oxygen, practically let go of their original forms of combination; but just when and how, and what the conditions are, is a little difficult as yet to understand. They form in the finished coke new and unusual compounds which are far removed from what they were in the coal. They are not chemical compounds in the usual sense, and bear little relation to anything we know in the way of chemical compounds. They do not conform to any rule of definite proportion, but come nearer perhaps to some of the attenuated stages of what, for lack of any better term, we may call an absorbed condition. As an illustration, sulphur can be made to unite with a coke which has absolutely no sulphur in it at all, like sugar carbon, in just about the amount that we find it in coke. There is no sulphur in the sugar carbon, but a compound of sulphur and carbon can be made which is stable at 1,000°C., or at any temperature. Similarly, a nitrogen carbon can be made at 1,000°C., starting with coke that has absolutely no nitrogen in it. Apparently oxygen also behaves in the same way. These new compounds are possibly physical rather than chemical.

Character of the Tar Oils.*—A great deal remains to be found out regarding the character of low-temperature tars, hence it is only possible to make some very general statements. Moreover, different coals produce tars which differ, presumably, in conformity to the type of organic matter which entered into the original deposit. Or, to put it more directly, the oxygen percentage in the coal governs, to a considerable extent, the type of tar produced.

This perhaps can be illustrated by the results recently obtained on a lot of coal from Utah. These coals are very high in resins and relatively low in that form of bituminous matter which is a large factor in the coking of the coals from regions further East. In Illinois, again, the oxygen content is not so high, but very much higher than in the high-volatile coals of West Virginia. The tar acids follow, in a general way, this content of oxygen; the higher oxygen coals giving a higher percentage of tar acid in the low-temperature tars.

As to the composition of the tars distilled from coal at different temperatures. Parr's experience leads him to believe that the percentage of tar-acids produced by low-temperature carbonization is not materially different over temperatures within the range of the low temperature zone, that is to say below 600°C. There is every reason to believe that secondary decompositions are almost absent at these low temperatures, and the type of tar discharged at 350° is substantially the same as that discharged at 450°, and also at 550°. At the latter temperature the discharge of tar ceases, but it is not different in composition from the tar discharged at first.

* Private communication from S. W. Parr, January, 1921.

The suitability of these tars for creosoting purposes has not been really determined, probably for the reason that they have not been available in sufficient quantities, but the high percentage of tar acids, mainly of the cresol type, would seem to point in the right direction; although present-day conclusions ascribe the effectiveness of creosote oil not so much to the tar acids as to the presence of unsaturated compounds, which readily become oxygenated, thus assuming more stable form and insuring the permanency of the creosoting substance in the wood. There is no question but that these low temperature tars have far more of the unsaturated compounds present than the tars from the ordinary process, and they are quite as active in this line when produced at the initial temperature as when produced at higher temperatures within the range of so-called low temperature distillations.

Researches of Pictet.—Some research work of considerable interest has been done more recently by A. Pictet,* Professor of Chemistry in the University of Geneva, Switzerland, and several co-workers. Studies have been made in connection with the distillation of coal at low temperature in a vacuum, and on the composition of the tar obtained, as well as the composition of the coal substance itself. He observes that the chemistry of coal still presents considerable blanks which are attributable to the insufficiency of the means for investigation, only two processes being available: (1) fractional distillation and (2) the action of solvents. The difficulties are: (1) that coal is not volatile without decomposition and (2) it does not dissolve easily in any known liquid.

When coal is distilled at atmospheric pressure, as is practiced in gas works and in coke plants, it is necessary, in order to extract all the volatile constituents, to heat it to a very high temperature (800 or 1,000°C.). The volatile products have undergone, due to the high temperature to which they have been subjected, various transformations, the nature of which is not entirely clear. It has not been possible to deduce from their chemical constitution any index as to the more complex compounds from which they have been derived.

There is only one way to avoid these transformations and that is to conduct the distillation at a much lower temperature and at a very reduced pressure. Several kilos of a fat coal coming from Montrambert (Loire) have been subjected to vacuum distillation. At a pressure of 15 mm. of mercury,

* The following condensed from "The Distillation of Coal in a Vacuum," *Chem. Met. Eng.*, Sept. 25, 1918, **19**, 415. Translation from *Revue Generale de Science*, October, 1916, **27**, 578–84.

distillation begins at about 100°C. and it is entirely terminated at 450°C., that is to say, a little above the point where it would begin if operated under ordinary pressure.

The products obtained are of an entirely different nature from those obtained by the ordinary processes. The gases have a different odor from illuminating gas, resembling that of butadiene and isopene. The coke is lighter, more friable and more easily combustible than ordinary coke. The tar, also is very different and represented about 4 per cent of the original coal. The water, about 1.6 per cent, does not contain ammonia and has an acid reaction.

The vacuum tar is the most interesting product and is a translucent liquid, light-brown, and has a light-green fluorescence; it is more fluid than ordinary tar and has an odor very different, resembling that of petrol. Immediately after its preparation, it floats upon the water which it has entrained, but it soon thickens, sinks and increases in density. At the end of 3 days, the density is exactly equal to 1; it rises again eventually. This phenomenon takes place when the air is excluded as well as in the presence of air; it is not, therefore, due to oxidation. In connection with this fact, it was observed that the tar, agitated soon after its preparation with an excess of solution of caustic soda, does not give up anything. Therefore it does not contain phenols, but the latter appear after a certain time and their quantity increases quite rapidly.

All the constituents of vacuum tar, whose nature these investigators have been able to determine, belong to the hydroaromatic series (naphthenes). The aromatic compounds of ordinary tar are replaced by their hydrides. The homologues of benzene make place for those of cyclohexane and cyclohexadienes, the phenols for the alcohol, the quinoline bases to their dihydrogenic derivatives. It is seen that these hydrides, when they are carried to a high temperature, have a tendency to lose a part of their hydrogen and to be converted into more stable aromatic compounds. It was then assumed that a phenomenon of this kind takes place in the gas retorts and that the hydrides of vacuum tar first form here and undergo, with a higher temperature, an immediate pyrolytic dehydrogenation. Vacuum tar would represent then an intermediate stage in ordinary tar formation.

This supposition was easy to verify by test. They took 200 grams of vacuum tar in its raw state, that is to say, not yet separated from its alcohols and bases, and caused it to run drop by drop into a red-hot iron tube, first filled with pieces of coke (in order to realize as much as possible the conditions of the gas retort). At the other end of the tube there were collected:

1. Gases (20 to 30 liters). These had the odor of illuminating gas and burned with a brilliant flame; they are composed of hydrogen and methane, accompanied by a little ethylene, but no acetylene.
2. Water strongly charged with ammonia.
3. A tar having the appearance and the odor of ordinary tar and from which they were able to separate benzene, toluene, xylenes, phenols, a small amount of naphthalene, anthracene and pyridine bases.

These are the principal constituents of ordinary tar. Their absence having been duly proved in the vacuum tar, the hypothesis suggested above seems to be justified; the hydrogen and the methane of illuminating gas, the ammoniacal water of illuminating gas, the phenols and the aromatic hydrocarbons of tar, are not at all the immediate products of the dry distillation of coal. They are only formed at high temperatures by the decomposition of other more complex volatile compounds, and in particular the more hydrogenated ones which are formed at a lower temperature.

This interpretation is in contradiction with the theory of Berthelot on the formation of coal tar. The latter theory consists in admitting that upon distillation the coal is decomposed entirely into very simple products—carbon, hydrogen, water vapor, ammonia, methane, ethylene, acetylene. On contact with the walls of the retorts, the last of these gases, notably acetylene, undergoes a series of polymerizations and condensations which give rise to the diverse aromatic hydrocarbons of tar.

They determined also the unexpected fact that it is possible to separate from coal, by simple distillation, a series of compounds which constitute an integral part of certain petroleums. It is the first time, apparently, that there has been found a relation of a chemical nature between these two natural substances. One point remains to be cleared up: Do the various compounds which form vacuum tar exist as such in the coal, or are they produced during the process of distillation? To be able to answer this question it is necessary to revert to the methods of exhausting coal by appropriate liquids.

It was found that there can be extracted from coal, by means of boiling benzene (80°C.), a series of hydrocarbons which are identical, or very analogous to, those yielded by vacuum distillation. This last operation then only separates them by simple volatilization, and it is safe to conclude that a part at least of the components of vacuum tar exist already formed in the coal.

They occur then as a solid hydrocarbon substance impregnated with a liquid chemically akin to petroleum. That this liquid has been formed through a slow decomposition of the solid mass, is the probable explanation, when we consider the formation of fire-damp which has been proved in all coal deposits, as well as the existence of the natural gas sources which are sometimes located in the proximity of these deposits.

The hydrocarbons, alcohols and bases which have been isolated and identified by Pictet and his collaborators have been tabulated from the translated article by the author. Some of these were separated from the vacuum tar and some from the benzene used as a solvent, as indicated by the letters T and B. Where the same substances have also been isolated from petroleum, the source of the petroleum is indicated in the right-hand column. The petroleums from California and Canada were investigated by Mabery* and the crude oil from Galicia by Pictet.

TABLE XLVIII.—SATURATED HYDROCARBONS, ETC.
Naphthenes or Cyclanes

Formula	Name	From tar or benzene	Petroleum containing same compound
C_6H_{12}	Cyclohexane (hexahydrobenzene)	T	
C_8H_{16}	Hexahydro xylene	B (?)	
C_9H_{18}	Hexahydro mesitylene	T & B (?)	Calif.
$C_{10}H_{20}$	Hexahydro durene	T & B (?)	Canada
$C_{11}H_{22}$		T & B	Canada
$C_{12}H_{24}$		T & B	Canada
$C_{13}H_{26}$		T & B	Canada
$C_{30}H_{60}$	Melene†	T	Galicia
$C_{13}H_{16}$	Hexahydro-fluorene	T	
$C_7H_{14}O$‡	Hexahydro-para-cresol (p-methyl cyclohexanol)	T	

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* *J. Am. Chem. Soc.*, **19**, 470; **25**, 267 and 276; **33**, 264.

† Identical with melene, which has been isolated from beeswax.

‡ Pictet gives $C_7H_{11}O$, which does not correspond to the alcohol named. The formula has, therefore, been corrected by the author.

UNSATURATED HYDROCARBONS, ETC.

Cyclo-Hexadienes

Formula	Name	From tar or benzene
C_7H_{10}	Dihydro-toluene	B
C_8H_{12}	Dihydro-meta-xylene	T & B
C_9H_{14}	Dihydro-mesitylene	T & B
C_9H_{14}	Dihydro-pseudocumene	T
$C_{10}H_{16}$	Dihydro-prenitene (?)	B
$C_{11}H_{16}$		B
$C_{14}H_{16}$		B
$C_{13}H_{12}$	Dihydro fluorene (?)	B

Alcohols and Bases

Formula	Name	From tar or benzene
$C_8H_{10}O$	Unstable alcohols of unknown structure	T
$C_9H_{12}O$		T
$C_{10}H_{14}O$		T
$C_{10}H_{11}N$	Dihydro-methyl-quinoline	T
$C_{12}H_{15}N$	Dihydro-trimethyl-quinoline	T

Bases of the hydro-pyridine series were found in the tar but were not isolated.

Coal Research in Germany.*—The German Coal Research Institute (Kaiser-Wilhelm Institute für Kohlenforschung) at Mülheim-Ruhr, has been carrying on extensive researches, under the direction of Franz Fischer, on the composition of coal and its distillation at low temperature. Collections of selected papers have been published† in three volumes covering the period from 1915 to 1918. Most of the papers in volume III deal with low-temperature distillation and investigations carried out with low-temperature tar or "Urteer," as Fischer proposes to call it. Several of the papers treat of the distillation of coal with benzene and other solvents under high pressure. Fischer's work with benzene as solvent is briefly described in Bone's recently published book on "Coal and its Scientific Uses."

In the reviewer's opinion, the three most important papers in vol. 3 treat of the behavior, under low-temperature distillation, of the coals of Upper Silesia, Westphalia and the Saar district.

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* Condensed from *Engineering*, London, Aug. 15, 1919, 217.

† By Verlag von Gebruder Borntrager of Berlin.

Those dealing with phenols, benzine, solar oil, etc., are also of special interest.

Lignite research has formed an important part of the work of the Institute and three papers on this subject have been published by Fischer and Gluud in the *Berichte*[*] which were written in 1917 and have not been published by the Institute.

The first of these describes a new method of low-temperature distillation. Different methods of dry distillation yield very different tars, owing to the low-thermal conductivity of coal; but in every case when the products of low-temperature distillation are required, it is necessary to work with thin layers of coal and to remove and cool the distillate quickly, to avoid exposure to volatilization temperatures. This has proved very difficult on a large scale, with rapid working. Fischer used a cylindrical slowly-rotating iron vessel, into which the pulverized coal was introduced through a hollow shaft. Inlets were provided for steam and outlets for steam and distillates. The apparatus was capable of treating 20 kg. of coal in one or 2 hr. An improved type of apparatus was subsequently described in vol. 3 of the Institute's collected papers (1918, page 253).

The primary products were naphthenes, highly viscous oils, and solid paraffin. Ordinary coal tar is not a primary product, but results from the decomposition, at higher temperature, of the primary products.

The second and third papers, in the *Berichte*, treat of paraffin from coal, its chemical composition and fractional distillation. By distillation at low temperature coal, can be made to yield very considerable quantities of light hydrocarbons (benzine) hitherto obtained almost exclusively from mineral oils, as distinguished from benzene (benzol), which is produced at high temperatures.

It is of interest to note that another coal research institute has been established at Essen by the Gesellschaft für Kohlentecknik. Its main policy will be commercial and industrial, the purely scientific field being covered by the older Institute at Mülheim.

Gas-producer Retorts.—Lloyd[†] contrasts German with English and American methods for the distillation of coal at low temperature. He points out that in the latter countries the production of smokeless fuel has furnished the primary incentive for develop-

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[*] *Berichte der deut. chem. ges.*, **52,** 1,035–1,068 (June 14, 1919).

[†] S. J. Lloyd, *Chemical Age*, January, **1921,** 16.

ment work in this direction, while in Germany the main desideratum has been to render the country less dependent upon foreign supplies of petroleum products and, particularly, motor fuel and lubricants. He reviews Gluud's monograph of 70 pages "(Die Tieftemperaturverkokung der Steinkohle"), which states that over 100 installations of modified producers are in operation (1919) throughout Germany, all of them yielding the characteristic volatile products of low-temperature carbonization but consuming the solid residue.

Gluud's description of this type of producer (made chiefly by Ehrhardt and Sehmer, Saarbrucken) is very brief. It seems to consist merely of an ordinary producer fitted with tubes through which the coal descends towards the base, where it is consumed. The net result is that the coal in its descent through the producer is kept out of contact with the hot producer gases as they ascend, and hence is not overheated. Also the products of distillation (tar, etc.) are kept separate from the products of combustion, so that it is not necessary to separate the former from a tremendous volume of nitrogen and carbon monoxide.

One advantage of this method of producing low-temperature products is that it does not involve the scrapping of existing producers. They may very easily be rebuilt with tubes, and without much loss of time. Gluud estimates that the remodeling of all such producers would bring on the market in a short time half a million tons of low-temperature tar, from which motor Spirit, lubricants, etc., might be extracted.

The only other practicable method of low-temperature carbonization mentioned by Gluud likewise recovers the volatile products only. This consists in a modification of the ordinary Mond producer, whereby the temperature is kept down within the proper limits by the use of excessive quantities of steam. These are made by Thyssen (Mülheim, Ruhr). Here the products of distillation leave the producer mixed with the combustion gases and the separation is sometimes not easy.

A more detailed account of some recent German producers of this type is given by Gluud in a second edition of his monograph.* The apparatus is being built by the A. G. für Bren-

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* Published by William Knapp, Halle, 1921. Excerpt from "Present Status of Coal Carbonization at Low Temperatures," by J. D. Davis, Fuels Chemist, U. S. Bureau of Mines, Pittsburgh, Pa. Serial No. 2292, Nov., 1921. This report gives a concise review of the subject.

stoffvergasung, Berlin, N. W. (40 Roou strasse 4), and also by the Dutch Mondgas a. Nebenprodukten, Ges., m. b. H. Berlin. "The machine of the Brenstoffvergasung Company is an ordinary gas producer with a rotating top. Attached to this is an annular iron retort extending downward into the body of the generator with means provided for retaining the charge and feeding it uniformly over the surface of the fuel bed in the generator as carbonization is completed.

A hopper, similar in design to the charging bell of a blast-furnace, serves to admit fresh coal as required to the retort. The retort is heated partly from the outer surfaces by conduction from the hot generator gases and partly by direct contact with a portion of the generator gas which is drawn through it. About one-third of the generator gas is by-passed through the retort for this purpose; and after the usual scrubbing for low-temperature oils, it is reunited with the main supply which comes directly from the generator. It is claimed that the loss of gas due to precarbonizing the coal can be replaced with an additional 10 per cent of raw coal or even less.

The improved Mondgas machine has a bell-shaped low-temperature retort built into the stationary generator cover and extending vertically downward into the generator body. The heating is done in the same manner as in the machine of the Brenstoffvergasung Company just described. Stirring of the charge and a uniform feed of coked residue are maintained by means of a gear-driven stirrer and distributor mounted axially in the retort. With this arrangement, coking of the coal is completed in 2½ hours and the generator gas contains "hardly traces" of tar; whereas, without stirring of the charge, the coking time is 3½ hours and even then the generator gas is dirty.

The gases were compared for two parallel runs with brown-coal briquets, the low temperature retort being operated in the first test and not in the second. In the second test 9 per cent more gas was obtained, but it contained more tar and water (80 grams of water and 5 grams of tar per cubic meter); whereas in the first test the total gas obtained from generator and low-temperature retort contained only 30 grams of water and 3 grams of tar per cubic meter. The heating value of this gas was about 1.5 per cent higher than that of the gas obtained by direct gasification. It would seem that this process might with profit be investigated further for the manufacture of industrial gas in this country. A clean, dry gas is always to be desired, and it does not appear that the scrubbing of the gas in this process presents much difficulty. Furthermore, it is only necessary to scrub one-third of the gas produced. The process might even prove applicable to our western lignites.

The Experiments of Loomis.—The Loomis-Pettibone gas producer was the most successful pioneer among producers for making clean gas from bituminous coal. It is of the downdraught type and was originally intended for making clean gas for internal-combustion engines.

Burdett Loomis, during the later years of his life, became much interested in the problem of carbonizing bituminous coal and making a moderately rich gas for general distribution by a simpler method than that ordinarily used. Some 20 years ago, while experimenting with producers, he passed a stream of hot raw-producer gas through a tank filled with bituminous coal and succeeded in making a hard coke of excellent quality. Further experiments indicated the possibility of reducing the time required for coking to considerably less than is required in coke-oven practice, owing to the more uniform distribution of the heat throughout the mass of coal; also, the possibility of making coke from raw wet peat by passing through it a stream of hot blast furnace gas. The sensible heat of the gas first dried the peat and then coked it, the volatile matter serving to enrich the original gas for fuel purposes.

Later, Loomis made some preliminary experiments with a view to developing a commercial method for the distillation of bituminous coal, with a stream of hot neutral gas. The gas would be initially warmed by passing it through the hot carbonized product, before discharging the latter from the retort, and then through a stove. Water gas could be used, at least in starting, or coal gas could be tapped from the outgoing stream, after cooling and scrubbing it in by-product recovery apparatus.

This method could be applied at any temperature, including a temperature just below the fusing point of the coal, in the range between 600 and 900°F. (315 to 480°C). By working at these temperatures, it was claimed, the hydrocarbons could be removed in the form of fixed gases and light oils without the formation of tar or heavy oils. The oxygen content in coals of low rank could be greatly reduced and the physical structure of the coal was not visibly altered. This was the result of avoiding fusion.

Small quantities of Nova Scotian slack, from gas coals, were treated by this method and the volatile content reduced to approximately 20 per cent. The author pulverized some samples in a mortar and found that this could be done as easily as with raw bituminous coal, whereas semicoke, which had been made by the distillation of bituminous coals by another low-temperature process, but above the fusion point, was harder and more difficult to pulverize. This product, therefore, was practically an artificial semibituminous coal. Loomis considered it a semi-smokeless fuel and proposed to briquet it by the application of heat and pressure, and without extraneous binding material, sufficient tar remaining for this purpose.

Loomis also proposed to apply his method to the distillation of lignite, oil shales, wood and other vegetable materials, as well as to oils. In the latter case, hot gas would be introduced from above, through a large number of vertical tubes projecting down into the oil, the gas being discharged near the bottom of the still and allowed to bubble up through the liquid. The main idea was to heat solid or liquid substances rapidly and to carry off the vapors or gas quickly and before secondary decompositions could take place. The gas would be used in a closed circuit, thereby avoiding the loss of oil vapors and conserving heat.

Unfortunately, Loomis died* before he had an opportunity to carry out further experiments on a commercial scale, as he had planned to do with the aid of Pettibone. It is impossible, therefore, to draw any very definite conclusions as to the merits of his very interesting theories.

One of the principal points raised by critics of this general method is that, when a part of the outgoing gas is recirculated, it will be cracked into a leaner gas on its second passage, and this will require larger and more expensive scrubbing equipment. Some other experimenters have overcome this limitation by the use of superheated steam as a heating medium (E. C. Evans, pp. 395 to 397). The fact that the volatile matter was distilled at temperatures below the intumescing point is of interest in connection with the Trent process (page 629).

It would appear that the use of a hot neutral gas by the method suggested by Loomis for distilling oils, could be advantageously applied to the distillation of coal tar. The troublesome deposit

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* In July of 1919, at the age of 81.

of carbon on the interior of the still might be made to form in a more easily removable condition, since the pipes could be withdrawn for cleaning.

Loomis, while not a man of scientific training, nevertheless formed some definite theories in regard to the general mode of formation of the hydrocarbon distillates which were based on observations during the course of his many years of practical experience with coal. He maintained that the hydrocarbons were first distilled in the form of the simpler gases and vapors, and that they could be removed rapidly by this method of heating and before polymerizing reactions took place, which resulted in the formation of heavier oils and tar during the subjection of the gases to higher temperatures.

It is of interest to note that Loomis' theory is in line with the recent experimental work of Zanetti* on the formation of aromatic hydrocarbons by pyrogenetic reactions among the simpler ones.

Internal-heating Processes.—The simplicity of the internal-heating method, and the possibilities which it offers for increasing the rate of heating of a mass of material, make it seem likely that it will, in time, come to have a definite field. The maximum rate of heat transfer to a mass of coal may, obviously, be attained by a combination of internal and external heating, as practiced by Parr and Olin. Whether Loomis' theory of being able to distil off the volatile matter, largely in the form of fixed gas, is practical or not, it is evident from Parr and Olin's experiments that the tar oils may be recovered in processes where internal heating is used. In general, it may be added that this method gives complete control over the pressure, temperature and atmosphere within the retort. These factors, in their various changes, control the reactions, both physically and chemically, of distillation, thereby affording a maximum latitude in the way of modifying the products to suit the demand.

The Doherty Process.—A new gas-making process has recently been developed by the engineering organization of Henry L.

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* Consult "Aromatic Hydrocarbons from the Thermal Decomposition of natural Gas Condensate," by J. E. ZANETTI and G. EGLOFF, *J. Ind. Eng. Chem.*, **9**, 474, May, 1917; "The Formation of Anthracene from Benzene and Ethylene," by J. E. ZANETTI and M. KENDELL, *ibid.*, **13**, 808, March, 1921; and other papers.

Doherty & Co.* It is the author's understanding that methods similar to those mentioned above have been given a trial, in connection with a two-stage process. A charge of raw coal is distilled at low temperature and the residual semi-coke is then gasified; both operations being conducted in the same retort.† The rich gas distilled from the coal during first stage is mixed with the water gas made during the second stage. The resulting mixture is a gas of sufficient richness for industrial or domestic use, having a calorific value of somewhat less than 500 B.t.u. per cu. ft.

It is planned to apply this gas, at first, to industrial uses under the name of "Carbogas." In a modification of the plan, another product will be manufactured under the name of "Hydrogas" which may be used on a more limited scale. It is claimed that the process requires an investment of only $1,500 per ton of daily coal capacity, as contrasted with an investment of from $4,000 to $10,000 in the types of plants now used in the manufacture of gas.

The Bussey Process.‡—Another type of internal-heating process employs the principle of the static type of gas producer but with this difference: the charge of solid fuel is fed through more rapidly and is carbonized instead of being completely gasified. Some experiments of this kind have been carried out by McLaurin§ in Glasgow, Scotland, as mentioned on page 400.

Another apparatus of this type, patented by C. C. Bussey‖ of Brooklyn, N. Y., in 1916, is shown in Fig. 88. This diagram is taken from the patent and shows a chain grate at the bottom for removing the coke. This has since been superseded with a different arrangement of grates. The shell of the retort is constructed in the form of a truncated cone in order to facilitate the downward feeding of the charge and to allow for the expansion which accompanies the disengagement of gas. The retort is kept completely filled and a fire is maintained on the grate

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* Editorial by F. W. Parsons concerning an interview with Henry O. Loebell, Industrial Fuel Engineer for Henry L. Doherty & Co., *Gas Age-Record,* Dec. 31, **1921,** 873.

† H. C. Porter, *J. Ind. Eng. Chem.,* Jan., **1921,** 50.

‡ Information furnished by W. E. Barrett, Consulting Engineer, 25 Broad St., New York, N. Y.

§ *J. Soc. Chem. Ind.,* **1917,** 620.

‖ U. S. Patents Nos. 1191869 and 1191870, assigned to the Coal By-Products Co.

which consumes some of the residual volatile matter in the coke, with the formation of a kind of producer gas. The hot gas rises through the superimposed charge until it is exhausted by a blower (45) after leaving the retort by pipe (44) located a short distance below the top.

The charge is heated by the sensible heat in the gas, as in the case of the processes already described, but with the difference that the gas distilled from the charge is diluted by the products of combustion. As the coal descends downwardly into zones of progressively increasing temperature, it does not reach the pasty stage until it is subjected to a considerable static pressure from the weight of the superincumbent material. This prevents the frothing and swelling of the fuel, as in the case of Parr and Olin's experiments (page 414), and results in the formation of a hard and dense coke which comes out in lumps; a few samples, inspected by the author, were from 4 to 6 in. across.

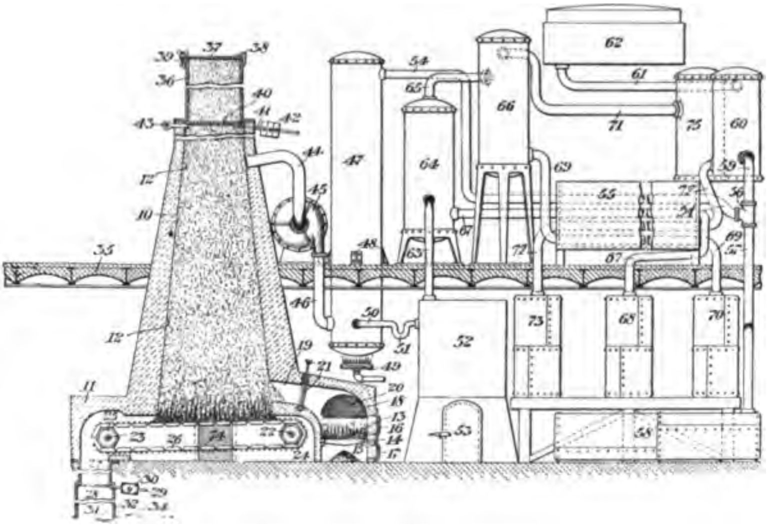

FIG. 88.—Method of extracting volatiles from coals, shales, lignites, and similar materials and for refining the same (C. C. Bussey, United States Patent 1,191,869, July 18, 1916).

The gas is cooled to condense the tarry vapors and to recover ammonia. The tar, upon distillation, yields valuable oils with a high tar-acid content, including creosote and other fractions. This is, in effect, another type of by-product gas producer in which the coal is fed through too rapidly to allow the fire to develop a high temperature or to burn the coal to an ash. The process is continuous and the time required for the passage of a portion of the charge through the retort, in the tests already made, was 5 or 6 hr. and the temperature developed was about 540°C.

Figures 89 and 90 show an experimental retort of this type which was built in Brooklyn, N. Y., for making tests for the U. S. Navy, during the war, to determine the practicability of extracting oil from cannel coals. Samples of the coal are shown lying on the ground about the retort. The analysis is given in Table XLIX.

FIG. 89.—Experimental Bussey retort at Brooklyn, N. Y.

TABLE XLIX

Moisture, per cent	2.69
Volatile matter, per cent	41.22
Fixed carbon, per cent	47.62
Ash, per cent	8.47
Sulphur, per cent	0.76
B.t.u. per pound (dry)	13,852

Yield of Products from 2,000 Lb. of Coal

Test made in February, 1919.	
Gas	70,000 cu. ft., 150–160 B.t.u. per cubic foot.
Efficiency	89 per cent.
Test made in April, 1919.	
Theoretical coke	1,121.7 lb.
Actual coke	997.3 lb., 12,283 B.t.u. 1 lb.
Oil	45.5 gal. or 372.8 lb.; sp. gr. = 0.985.
	(1 gal. = 8.201 lb.; 17,501 B.t.u. per pound.)
Gas	43,000 cu. ft.; 131.8 B.t.u. per cubic foot.
Ammonia (concentrated)	4.95 to 7.98 lb.

Fig. 90.—Experimental Bussey retort at Brooklyn, N. Y.

The producer gas should be useful as boiler fuel. The capacity of one retort is about 24 tons per day.

A brief test was made with bituminous coal, in January, 1920, which showed that the resulting coke was of very similar quality to that obtained by carbonizing cannel coal. It is also claimed that this process will be especially applicable for the distillation of lignite and oil shale at low temperature. The auxiliary fire (13) in Fig. 88 is intended for use in connection with these less easily combustible materials.

Rotary Retorts.—Horizontal rotary retorts have been tried by a few experimenters; but when the heat is applied externally, it adds another problem, the expansion of the metal walls. A retort of this type, however, has been designed by the Kennedy Van Saun Engineering & Manufacturing Co., with provision for free expansion; the mechanical details being based on the designer's experience in building cement kilns, tube mills and rotary driers.

The General Gas Reduction and By-Products Co. has made an experiment with one of its rotary gas producers (Fig. 83, and page 336) and found that this type of machine has possibilities for carbonizing lignites and middle western coals. This was effected by completely burning a part of the lignite, and resulted in the evolution of a good volume of gas having a thermal value of 156 B.t.u. per cubic foot, and the recovery of about 89.5 per cent of the original carbon in the residual.

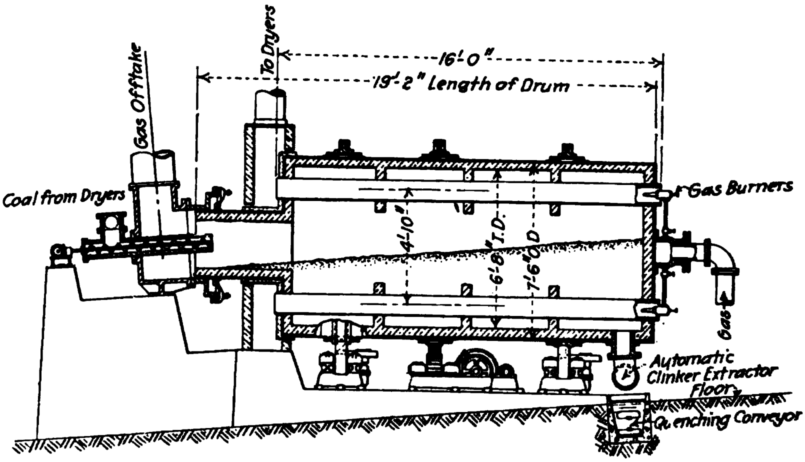

FIG. 91.—Rotary retort for carbonizing lignite. Internally heated by burning gas in tubes.

By returning part of the fixed gas through the tuyeres, an inert heated atmosphere can be maintained. A rotary retort, for the application of this principle, has been designed and is illustrated in Fig. 91. The company has based this design on its experience with the rotary gas producer and has added a novel feature for applying the heat internally, and without diluting the gas. A part of the gas is burned in metal tubes located just within the shell of the retort. These may readily be replaced if burned out, but it should be possible to lengthen their life by calorizing the inner surface.

A rotary retort was used by Parker in the early experiments in the coalite process, in England, and apparently was abandoned because it maintained the material in a powdery condition, just as when the raw coal is introduced. This fine product, however, should be useful as granulated fuel, or for making briquets, as well as for making pulverized fuel.

Some recent experiments with a rotary retort have been made by E. Roser, in Germany, with the object of obtaining semi-coke for subsequent complete gasification in a producer* (see also page 430). The retort is built like a cement kiln and the experimental unit, having a capacity of 50 tons of coal per day, has been working continuously since the middle of 1919. It was designed, constructed and installed by Thyssen & Co., A. G. Maschinenfabrik. The charge is propelled through the retort by means of a worm.

The products obtained from the distillation of a metric ton of gas coal are as follows:

PRODUCT	YIELDS		HEAT VALUE
Semi-coke	650 kg.	(1,430 lb.)	6,000 cal.
Tar	100 kg.	(220 lb.)	8,600 cal.
Light oil	30 kg.	(66 lb.)	10,000 cal.
Oven gas	150 cu. m.	(5,296 cu. ft.)	7,000 cal.

The coal was from the Gewerkschaft Friedrich Thyssen, Lohberg, and had a heat value of 6,800,000 cal. per ton. The total calorific value of the products is 6,110,000 cal. so that the gross thermal efficiency of the process is about 90 per cent. The fuel required for heating the retort is not stated.

Carbonization in Molds.—Small cast-iron molds have been used as containers for the granulated raw coal by a number of experimenters, and these have been conveyed through a furnace at a slow speed, as mentioned on page 402. A process of this type has been applied to Illinois coals by G. W. Traer.† The containers were 4 ft. long, 4 ft. high and 1 ft. wide, and they were divided into compartments from 4 to 8 in. wide and with partitions 34 in. thick for conducting heat into the mass. They were mounted on wheels and run through the retort on a track, 8 hr. coking being allowed for a charge.

The semi-coke came out of the molds in solid bricks, of good

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* *Power*, Oct. 26, **1920,** 678.

† Low-Temperature Distillation of Illinois and Indiana Coals," by G. W. TRAER, *Am. Inst. Min. Eng. Bull.*, September, **1918.**

firm structure, and made an excellent smokeless fuel for domestic use and for locomotives. The volatile content was 18 per cent and the yield 77.5 per cent. The gas yield was only from 1,000 to 2,000 cu. ft. per ton of coal, while 25 gal. of light tar and oil were recovered.

A method of this type was among the first experiments tried by C. H. Smith, but it was abandoned in favor of the carbocoal process. The mechanical features do not appear to be very practical for a commercial process.

The Coalite Process.*—As previously noted, the development work which was started in England some years ago on the original Coalite process, and two other processes, is being continued by a new company under the name of Low Temperature Carbonization Limited. A plant has recently been built at Barugh, near Barnsley, Yorkshire, which is being operated on a commercial basis. Twenty retorts are now in continuous service and are carbonizing about 36 tons of coal per day. The fuel produced is a semi-coke carrying only a very small proportion of breeze, and of a suitable character for withstanding handling and transportation.

The general arrangement of the retorts is somewhat similar to that used in coke oven plants except that the coal is discharged from the bottom instead of from the side. They are built of firebrick, each retort having a depth of 9.5 ft.; a length, tapering from top to bottom, of 7.25 to 7.5 ft. and a width of 11 inches. The interiors have semi-circular ends. The distance, from center to center, is 21 inches. Inside each retort is a pair of collapsible plates of manganese cast iron, which occupy the central portion of the space, and the charge lies between them and the walls in two layers, each about 3.5 inches thick. The gases escape through perforations in the plates and rise through the comparatively cool space between them.

Processes with Feed-screw Mechanism in the Retorts.—The carbocoal process employs horizontal retorts which are heated, mainly, on the under side. The charge lays in a shallow layer on the bottom and occupies only a relatively small fraction of the volume of the retort. A pair of rotating shafts extend through the center of the retort and carry a series of inclined paddles for stirring the charge and advancing it through the retort.

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* Abstract from "The Manufacture of Smokeless Fuel," *Engineering* (London), **62**, **596** (Oct. 28, 1921)

The Greene-Laucks process employs a vertical cylindrical retore containing a hollow rotating worm for performing the same functions. The charge completely fills the annular space between the hub and the walls of the retort. These two processes have been further developed than any of the foregoing, so that more complete data is available.

THE CARBOCOAL PROCESS*

An elaborate series of experiments has been conducted during the past 5 years at Irvington, N. J., which has resulted in the perfection of a process for the manufacture of smokeless fuel from bituminous coals, and for the recovery and refinement of the coal-tar products. These experiments have been carried out by the International Coal Products Corporation under the direction of Charles H. Smith, the inventor of the process. The company has been operating the large experimental plant

Fig. 92.—Experimental plant of the International Coal Products Corporation, at Irvington, N. J.

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* References: "Carbocoal," by C. T. Macolmson, *Am. Inst. Min. Eng., Bull.* May, **1918**; and "Carbocoal Development is Most Timely," *The Black Diamond*, Oct. 25, **1919**. See also "Low-temperature Carbonization," by H. A. Curtis, *Chem. Met. Eng.*, **23** (1920), No. 10; and "The Commercial Realization of the Low-temperature Carbonization of Coal," by H. A. Curtis, *J. Ind. Eng. Chem.*, **13** (1921), No. 1, 23.

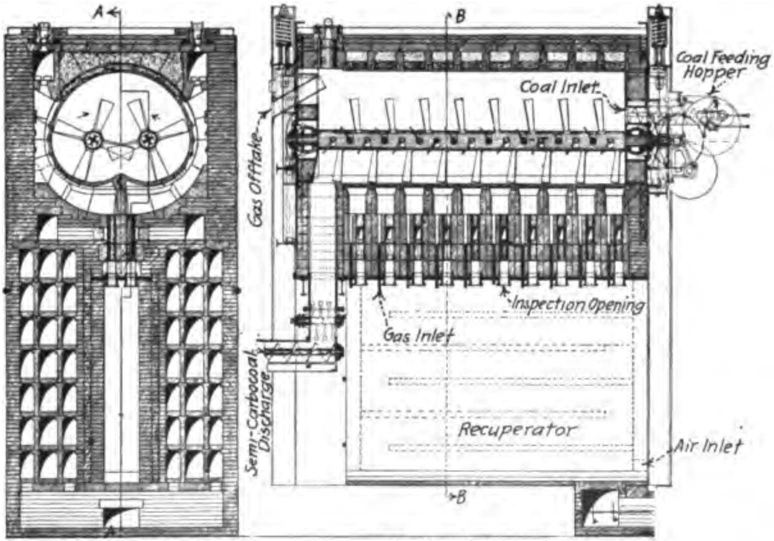
shown in Fig. 92, and has been producing and marketing the products on a commercial scale. The fuel is called carbocoal and is prepared in briquet form, as shown in Fig. 93.

Description of the Process.—The complete process consists of four main features: (*a*) the distillation at low temperature of the crushed raw coal, (*b*) the briquetting of the carbonized product from this distillation, (*c*) the distillation at higher temperature of the briquets, and (*d*) the recovery and refinement of by-products from both distillations.

(*a*) *Primary Distillation.*—Coal, preferably of the high-volatile type, is crushed and fed, by means of continuous-screw feeders, into specially designed retorts. In these retorts, the coal is distilled at a temperature of about 850 to 900°F. (450 to 480°C.). The coal is constantly agitated and mixed during the entire operation. This is accomplished by a twin set of paddles which also advance the charge through the retort. By this means, all portions of the charge are uniformly distilled and, by controlling the speed at which the charge moves through the retort, the distillation may be arrested at any desired stage. As only a partial carbonization is permitted in the primary distillation, the hard metallic cells characteristic of coke are avoided. The period of primary distillation is in the neighborhood of 3 hr. and each continuous retort has a carbonizing capacity of 24 tons per day. Figure 94 is a view of the feed end of a bank of retorts and shows the mechanism for driving the paddles. Figure 95

FIG. 93.—Pile of carbocoal briquettes.

FIG. 94.—Arrangement of automatic feed of primary retorts of carbocoal plant of Clinchfield Carbocoal Corporation, South Clinchfield, Va.



Section B-B Section A-A

FIG. 95.—Primary retort and recuperator, for making semicarbocoal.

shows the details of the retort. Gas, tar and ammonia products are recovered and the volatile content of the original coal reduced to the desired point of, say, about 10 per cent, leaving a carbonized product, termed semi-carbocoal, which is of light, soft structure and suited for smokeless combustion.

The preliminary crushing of the coal is done in a hammermill, which reduces the coal to a finely divided state. The agitation of the charge brings the individual particles into contact with the heated lower wall of the horizontal retort. This results in a much more rapid distillation of the volatile matter than can take place in the usual high-temperature processes, where the charge is stationary and the heat transfer to the interior portions of the charge takes place by slow conduction through a considerable mass of coal in the various stages of distillation. Also

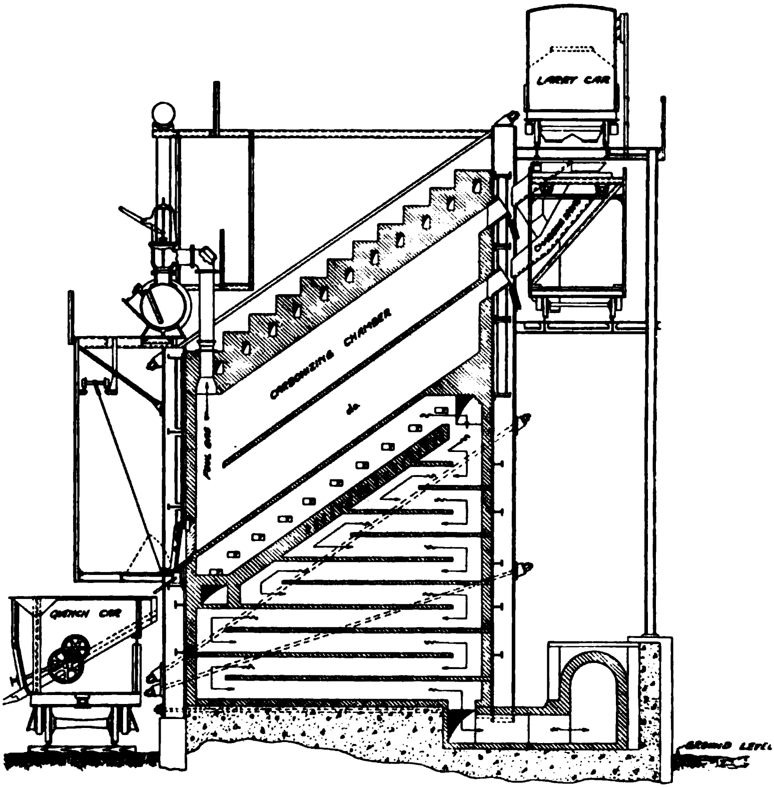


Fig. 96.—Cross-section of secondary retort in the production of carbocoal.

the vapors evolved are free to escape rapidly from the zone of maximum temperature. This results in the recovery of a large proportion of the hydrocarbons in the form of valuable oils, rather than as fixed gases.

(*b*) *Briquetting.*—The semi-carbocoal, after being quenched and crushed, is mixed with pitch recovered from the tar yield, and then briquetted by roll presses.

(*c*) *Secondary Distillation.*—The briquets are conveyed to the secondary retorts, in which they are carbonized at a temperature of approximately 1,800°F. (980°C.). This distillation yields carbocoal, additional gas, tar and ammonia liquor. All evidence of the pitch as a separate ingredient disappears, the volatile matter of the pitch being driven off and the carbon remaining in the briquet, thereby increasing the carbocoal yield. There is a marked shrinkage in the volume of the briquet, with a corresponding increase in density, but no distortion of its shape. The distillation requires about 6 hr. and is performed in an inclined retort, using gravity charge and discharge. The capacity of these retorts is approximately 60 to 75 tons of raw briquets per day. A section of the retort is shown in Fig. 96.

(*d*) *Tar and Gas Recovery.*—During both distillations gas, tar, and ammonia are recovered by standard by-product recovery apparatus.

Carbocoal.—A representative proximate analysis of carbocoal is given in Table L. The coal is from the Clinchfield district in Virginia.

TABLE L

	COAL	CARBOCOAL
Moisture	0.72	1.84
Volatile matter	35.01	2.75
Fixed carbon	57.23	85.64
Ash	7.04	9.77
	100.00	100.00
Sulphur	0.63	0.52

The amount of ash and sulphur in the carbocoal depends upon the characteristics of the coal from which it is made. The summarized proximate analyses of carbocoal, manufactured from 25 different coals at the Irvington plant, are shown in Table LI.

Table L shows the proximate analyses of carbocoal and of the coal from which it was made.

TABLE LI.—ANALYSES OF CARBOCOAL

	From run-of-mine, per cent	From washed coal, per cent
Moisture	1.00 to 3.00	1.00 to 3.00
Volatile matter	0.75 to 3.50	0.75 to 3.50
Fixed carbon	82.00 to 88.00	85.00 to 90.00
Ash	8.50 to 12.00	7.00 to 10.00
Sulphur	0.50 to 1.50	0.60 to 1.50

TABLE LII

All results computed on a dry basis

Coal					Carbocoal				
Volatile matter	Fixed carbon	Ash	Sulphur	B.t.u.	Volatile matter	Fixed carbon	Ash	Sulphur	B.t.u.
32.50	63.70	3.80	0.79	15,182	2.38	91.71	5.91	0.60	13,668
33.80	59.99	6.21	1.91	14,401	2.16	88.61	9.23	1.31	13,168
36.90	60.05	3.05	0.65	14,587	4.88	88.49	6.63	0.52	13,606
39.70	57.44	2.86	0.66	14,600	5.30	87.99	6.71	0.55	13,799
40.40	53.60	6.00	2.54	13,807	3.21	86.81	9.98	1.98	13,087

The percentage of by-products recovered from clean coal is greater than that recovered from high-ash coals; therefore, the careful preparation of the raw coal by washing, or other means, is profitable.

Carbocoal is dense, dustless, clean, uniform in size and quality, and can be readily handled and transported long distances without disintegration. It is grayish black in color, slightly resembling coke, but its density more nearly approaches that of anthracite. The density of well carbonized briquets is given in Table LIII. For comparison, the author has measured the density of anthracite, from the northern district in Pennsylvania, as well as that of a good grade of coke which was made in by-product ovens from Appalachian coals.

Carbocoal briquets can be made in any size, from 1 oz. to 5 oz. The 2½-oz. briquets have proved to be the best for general purposes, especially for domestic use. The Navy prefers a 1-oz.

TABLE LIII

	CUBIC FEET PER TON (2,000 LB.)
Anthracite:	
Stove and egg mixed	38.4
Egg	38.7
Stove	38.4
Nut	38.1
By-product coke:	
Stove and egg mixed	71.1
Egg	71.1
Stove	66.7
Carbocoal:	
2½-oz. briquets	43.0

briquet, due to low vacuum and hand-firing, while the ideal locomotive fuel would be a briquet weighing around 5 oz. This heavy briquet is necessary in order that the fire will lay properly, as the vacuum created in the firebox of a modern locomotive runs very high, even as much as 15 in.

Heretofore, devolatilized fuels, such as coke, have not attained the high rates of combustion desired for locomotive, marine and general steam purposes; and their greater displacement has operated against their general use where transportation cost or stowage space has been an important factor. Carbocoal overcomes these objections. It is actually a relatively soft but tough form of carbon, readily attacked by oxygen in combustion; and for this reason requires much less draft than other high-carbon fuel.

Carbocoal has been tested by several railroads and by the United States Navy. These tests have demonstrated that the fuel is smokeless, and the rates of evaporation per pound of carbocoal range from 8.5 lb. of water to 12.8 lb. (from and at 212°F.). The amount of coal burned per square foot of grate surface per hour ranged from 100 lb. in the former case, to 27 lb. in the latter. A maximum combustion rate of 166 lb. per square foot of grate surface per hour has been reached for a short period. It requires no greater draft than bituminous coal.

It has also been subjected to practical tests in household use for more than 3 years. It fulfills all requirements of a domestic fuel, burning satisfactorily without change of furnace or grates, and responding readily to changes in draft. The uniformity of combustion, absence of fines, even distribution of ash, and absence of clinker, as compared with the coal from which it is made, are additional characteristics in favor of this fuel. Carbocoal can be banked satisfactorily over night, and requires no more attention and the consumption is no greater than with anthracite. Carbocoal has been in great demand and sells on an even basis with the best grades of anthracite. In domestic use its cleanliness is a desirable factor and its applications include furnaces, stoves, cooking ranges and open grates.

It has also been found particularly suitable for stationary boilers, where smokeless combustion is desirable, and for various industrial applications where an intensive and uniform heat is required.

Available Coals.—The carbocoal process has been applied to both coking and non-coking coals. It has been found to work satisfactorily with the non-coking coals of Utah, Washington, Colorado, Illinois, Michigan and Kentucky; and the coking coals of Pennsylvania, Ohio, Virginia, West Virginia, Tennessee, and British Columbia. Through the application of this process, many of the black lignite or subbituminous coals of our Western States may be converted into a fuel of higher economic value.

The Tar and Its Products.—Coal containing 35 per cent of volatile combustible matter produces more than 30 gal. of water-free tar per short ton, and may be expected to give the yields shown in Table L. The net products are those available for sale after deducting those used in the process.

TABLE LIV.—YIELDS PER TON (2,000 LB.) OF COAL, 35 PER CENT VOLATILE CONTENT, BY TWO-STAGE DISTILLATION

Products	Units	Gross yield	Net yield
Carbocoal	Pounds	1,400	1,400
Dry tar	Gallons	30	
Light oils	Gallons	.....	3
Oil distillates	Gallons	.....	15
Pitch	....	12	
Ammonium sulphate	Pounds	20	20
Gas, 650–750 B.t.u.	Cubic feet	5,000	1,500
Gas, 300–350 B.t.u.	Cubic feet	4,000	1,000
Total gas, 600 B.t.u.	Cubic feet	(approx.) 9,000	2,500

The tar products recovered from the distillation of the coal, at the low temperature used in this process, are different in nature from those obtained in other processes where high temperatures are used. At the lower temperature, there is an abundance of tar vapors and a relatively small yield of gas of high illuminating value. At the higher temperature, these primary products are split up, with a consequent increase in the gas yield and a corresponding decrease in its illuminating value and in the amount of tar vapors recovered. There is also an increase in the percentage of residuals, the pitch increasing from 30 per cent in the low temperature distillation to 64 per cent or more when high temperatures are used.

The tar obtained in the primary distilloation f the coal has a specific gravity of 1.00 to 1.06. It contains a large percentage of light solvent oils, tar acids, and cresols, but very little carbolic acid and no naphthalene or anthracene. The free-carbon content of this tar is low. The light oils contain appreciable quantities of naphthenes, pentane, hexane, and hydrocarbons of the paraffin series, which make these oils valuable as motor fuels.

A satisfactory method of removing the paraffin and aromatic portions of the light oil has been developed, so that chemically pure benzene and toluene can be obtained by this process. During the low-temperature distillation period, 20 to 28 gal. of tar, including the light oil obtained from the stripping of the gas, are recovered, the exact amount depending upon the volatile content of the coal. This low temperature tar contains approximately 30 per cent of pitch and 70 per cent of tar oils, as compared with 50 to 60 per cent of pitch and 40 to 50 per cent of oil products contained in ordinary gas-house and coke-oven tar.

In the second or high-temperature distillation, 5 to 6 gal. of tar are added to the above yield. This tar is heavier than that obtained from the first distillation and is similar to coke-oven tar.

Table LV compares the tars and light oils obtained in the production of carbocoal with those obtained in the ordinary by-product coking processes.

In addition to the above yield of tar, there is obtained, in both the by-product coke oven and the carbocoal process, by stripping the gas, about 2 gal. of light oil. This yield depends upon the characteristics of the coal carbonized.

More than 30 per cent of the fraction from 170 to 360°C. are tar acids, the remainder being neutral oils. The various distillates run from 40 per cent of tar acid for the middle oil to 25 per cent for the heavy oil.

TABLE LV.—TYPICAL DISTILLATION OF COKE-OVEN AND CARBOCOAL TARS

Products	Distillation temperature, degrees Centigrade	Coke-oven tar		Carbocoal tar	
		Gallons	Per cent	Gallons	Per cent
Light oil	0–170	0.27	3.47	1.362	4.66
Middle oil	170–230	0.44	5.85	4.057	13.67
Creosote oil	230–270	0.78	10.37	3.432	11.57
Heavy oil	270–360	1.26	16.81	8.007	27.01
Pitch	....	4.66	62.18	12.782	43.09
Loss	....	0.09	1.32		
Total	....	7.50	100.00	29.66	100.00

The value of the products from the distillation of tar depends, of course, on the extent to which the tar is refined. The fractionation and subsequent treatment of the tar oils, which are parts of this process, give the products shown in Table LVI, in carbonizing 1,000 tons of coal; the figures are based upon data obtained from carbonizing run of mine coal from Clinchfield, Va., the analysis of which is given in Table LI.

TABLE LVI

1.	Carbocoal	700 tons
2.	Sulphate of ammonia	20,000 to 25,000 lb.
3.	Motor spirits	2,000 to 2,500 gal.
4.	Crude tar acids, principally cresylic acid	4,000 to 4,500 gal.
5.	Neutral oils	3,200 to 3,800 gal.
6.	Creosote oil	3,500 to 5,000 gal.
7.	Heavy creosote oil	5,000 to 8,000 gal.
8.	Surplus gas of 530 B.t.u., approximately	2,000,000 cu. ft.
9.	Pitch	10,000 gal.
10.	Gas of 530 B.t.u., approximately	9,000,000 cu. ft.

Pitch is always an element of questionable value in tar distillation. The complete process utilizes practically all its pitch for briquetting the semi-carbocoal produced by the first distillation. Moreover, the valuable portions of this pitch are recovered in the gas resulting from the second distillation and in the carbon in the carbocoal.

Value of Tar Oils.—The carbocoal process tar, owing to its low carbon content and its high yield of distillates, rich in tar acids, is intrinsically more valuable than other tars derived by higher-temperature carbonization. Mixed distillates derived from carbocoal tars are selling at the present time for 30 cts. per gallon.

A higher percentage of oils is recovered than is possible from tar produced by any high-temperature process, and the oils have a ready market at prices in excess of similar cuts of oil produced from other tars, on account of their high tar-acid content.

The oils are especially valuable for wood preserving and disinfecting purposes, as well as for disinfectants and insecticides, owing to the toxic properties of the tar acids.

Creosote Oils.—Pennsylvanian coals ranging in volatile content from 34 to 38 per cent yield approximately 9 gal. of creosote. While the analysis of the creosote is slightly different from the present specifications of the American Wood Preserving Association for creosote, it would be merely a matter of educating the creosote industry to recognize its value, as the creosote produced from carbocoal tar is superior in toxic value to the ordinary creosotes. It is a pure coal tar product and the company does not anticipate any trouble in having its product adopted by the wood-preserving industry. Oils produced by this process are overturning prejudices formerly held against oils produced from low-gravity tars; and wherever they have gone into competition with oils produced by the high-temperature process, they have won out, and, in many cases, the company has had its specifications adopted and has secured an advance in price over competitive oi.s.

Flotation Oils.—A superior flotation oil can be produced from the creosote fraction. The general specifications for flotation oil call for a specific gravity of not over 1.0, with a tar-acid content of 20–25 per cent. Creosote derived from these tars, which contain from 40–45 per cent. tar acid, can be diluted with an equal quantity of dead oil, giving as a result a flotation oil complying with the requirements, both as to specific gravity and tar-acid content.

The cut is the same as for creosote; consequently the yield of 9 gal. from a ton of Pennsylvanian coal, of 34 to 38 per cent volatile content, is also available as a source of flotation oil. To this should be added 9 gal. of dead oil, making a total of 18 gal. of salable flotation oil per ton of coal carbonized.

Lubricating Oils.—The world will in a few years see a great shortage of natural oils, especially those that can be used for producing lubricants, for which there is a most radical increase in demand due to the enlarging use of machinery, and especially of pleasure and business motors and farm tractors.

The following table gives a summary of the products obtained from small scale tests of different coals and lignites.

TABLE LVII.—INTERNATIONAL COAL PRODUCTS CORPORATION
Results from Tests of Various Coals and Lignites

Sample from mine	Moisture as received	Proximate analysis (dry basis)							
		Raw coal				Semi-carbocoal			
		% vol.	% F. C.	% Ash	B.t.u.	% vol.	% F. C.	% Ash	B.t.u.
American Coals									
Marrowbone, Ky......	2.22	36.60	58.42	4.98	14,786	9.45	82.87	7.68	13,686
Boyd County, Ky......	9.07	40.40	55.94	3.66	13,846	9.80	84.52	5.68	14,323
Boldman, Pike Co., Ky.	3.53	39.70	57.44	2.86	14,600	10.70	83.97	5.33	14,052
Whitwell, Tenn........	3.38	26.20	65.38	8.42	......	7.78	81.07	11.15	
Grand Ridge, King Co., Wash..............	16.00	42.64	46.08	11.28	......	12.69	71.04	16.27	......
Pittsburgh Terminal, Pa................	1.20	32.00	63.34	4.66	......	7.69	85.59	6.72	....
Clinchfield, Va.........	2.50	36.81	57.46	5.73	......	12.02	79.98	8.00	......
Dante, Va............	1.72	35.50	57.87	6.63	14,568	14.69	77.09	8.22	13,563
Red Jacket, Mattewan, W. Va.............	1.98	36.92	58.16	4.92	14,632	7.15	85.17	7.68	13,535
Chariton, Iowa........	17.37	39.70	49.97	10.33	13,189	14.56	70.51	14.93	11,627
Rock Springs, Wy., (lignite)............	12.10	39.88	52.47	7.65	12,228	11.69	76.96	11.35	12,670
Rockdale, Texas.......	26.35	45.21	41.50	13.29	11,055	11.67	67.05	21.28	10,039
Big Four, Colo. (non-coking).............	5.23	39.35	52.22	8.43	12,700	12.35	76.11	11.54	12,268
Walsen washed nuts, Colo. (non-coking)...	3.85	37.35	48.53	14.12	12,569	14.41	65.73	19.86	11,786
Ideal, Colo. (caking coal)...............	2.81	39.22	50.99	9.79	13,230	10.66	77.54	11.80	12,662
Zanesville, Ohio........	5.48	45.40	49.67	4.93	14,539	13.53	78.68	7.79	14,327
Newark, Ohio.........	4.09	44.80	48.84	6.36	14,000	11.55	78.02	10.43	......
Wenona, Ill. (caking)...	15.40	40.40	53.60	6.00	13,807	9.76	80.53	9.71	13,540
Saginaw, Michigan.....	9.63	38.40	54.82	6.78	13,565	11.93	78.30	9.72	12,694
Pittsburg, Oklahoma...	3.53	39.75	54.28	5.97	13,556	15.46	76.27	8.27	13,365
Versailles, Missouri....	3.56	44.30	44.95	10.75	14,000	10.64	72.15	17.21	12,376
San Miguel, California.	7.13	51.90	41.66	6.44	13,460	18.45	70.58	10.97	12,389
Rouse West, Colo. (non-caking)........	2.13	38.68	50.38	10.04	12,237	10.42	74.39	15.19	12,600
Canadian Coals									
Cadomin (coking coal).	3.04	25.64	61.79	12.57	13,472	7.30	76.28	16.42	12,132
Taylorton, Can. (lignite)..............	33.90	45.20	42.30	12.50	11,096	14.72	67.23	18.05	11,782
Nova Scotia (coking coal)..............	1.55	32.10	56.46	11.44	13,432	8.90	75.76	15.35	12,180
Ladysmith, B. C.......	2.6	37.30	53.59	9.11	......	11.70	74.89	13.41	......

POWER PLANT FUEL SUPPLY

One of the principal applications of the carbocoal process is for the preparation of fuel for power plants with the recovery of valuable by-products. The single-stage process is applicable for this purpose and consists of two main features: (*a*) the distillation of raw coal at low temperatures, and (*b*) the recovery and refinement of tar products.

Carbocoal				Yields (total products per short ton of coal (dry basis)					Test No.
% vol.	% F. C.	% ash	B.t.u.	Carbocoal, lbs.	Tar, gals.	Amm. sulphate, lbs.	Lt. oil from gas, gals.	Gas, cu. ft.	
2.18	89.52	8.30	13,320	1,300	38.08	21.48	1.57	7,657 (583 B.t.u.)	84
3.08	90.82	6.10	13,710	1,238	39.15	23.29	1.36	7,537 (604 B.t.u.)	82
5.30	87.99	6.71	13,799	1,316	42.12	23.22	1.48	7.914 (613 B.t.u.)	85
1.28	86.88	11.84	......	1,520	24.33	19.05	0.747	8,020	21
4.47	79.13	16.40	......	1,575	27.27	26.67	1.37	8,595	22
1.78	91.09	7.13	13,750	1,290	30.35	20.00	1.00	8,527	30
3.92	85.28	10.80	......	1,494	36.14	20.00	1.68	9,034	51
3.17	86.75	10.08	12,970	1,333	34.89	22.04	1.89	7,900 (612 B.t.u.)	102
1.62	90.00	8.38	12,840	1,300	37.84	18.40	1.61	9,209 (466 B.t.u.)	59
2.26	81.51	16.23	11,580	1,275	29.37	22.95	1.69	8.011 (575 B.t.u.)	90
2.75	84.41	12.74	12.223	1.238	19.68	25.7	1.20	8.742 (368 B.t.u.)	56
8.17	70.43	21.40	11,275	1,184	18.22	21.59	2.05	11,262 (359 B.t.u.)	58
7.18	80.07	12.75	12,800	1,234	37.32	20.90	1.44	8,932 (565 B.t.u.)	66
6.52	73.61	19.87	11,036	1,318	36.44	20.88	1.80	9,011 (552 B.t.u.)	70
6.93	79.01	14.06	12,358	1,280	38.44	26.09	0.93	8,380 (557 B.t.u.)	73
6.44	85.12	8.44	13,616	1,169	42.26	20.62	2.21	8,483 (576 B.t.u.)	109
8.33	81.37	10.30	......	1,268	34.32	22.42	1.87	9,129 (678 B.t.u.)	115
3.21	86.81	9.98	13,087	1,248	39.00	23.06	1.76	9,037 (646 B.t.u.)	86
2.62	86.63	10.75	12,110	1,268	35.7	20.6	2.24	8,657 (576 B.t.u.)	95
2.52	87.46	10.02	11,455	1,233	29.85	22.37	1.96	10,495 (499 B.t.u.)	101
3.01	78.31	18.68	12,109	1,149	44.67	20.39	3.63	8,053 (661 B.t.u.)	105
3.01	83.95	13.04	12,150	991	50.27	21.55	1.61	8,583 (536 B.t.u.)	107
3.52	81.19	15.29	11,834	1,370	35.12	19.95	2.08	8,233 (528 B.t.u.)	71
2.13	82.40	15.47	12,280	1,541	19.81	16.52	1.32	8,975 (416 B.t.u.)	63
3.54	79.65	16.81	11,870	1,387	16.52	24.70	2.07	13,452 (391 B.t.u.)	88
3.56	80.24	16.20	11,405	1,409	36.52	18.50	1.56	8,815 (555 B.t.u.)	94
3.57	82.95	13.48	......	1,334	32.65	20.00	1.62	8,185	28

The semi-coke produced in the low-temperature distillation is known as semi-carbocoal. It varies in size up to 3 or 4 in. and is light in weight, displacing 85 cu. ft. per ton. Its physical characteristics, smokeless and free-burning qualities, and freedom from coking in combustion, make it ideally suited as a steam fuel where high rates of combustion are required.

It may be burned in lump form on grates or it may be crushed to a suitable size for feeding into automatic stokers. Owing to the limitations common to carbonized fuels of light structure, it would seem to be best adapted for burning in pulverized form, especially when used on a large scale. The burning of carbonized fuels in finely divided form is discussed in Chapter VIII. For burning in small boiler plants, it should be an excellent fuel in its original form.

Table LVIII shows a comparison of the proximate analyses of semi-carbocoal, and the coal from which it was produced. The coal is the same as in Table L, except that the figures are compared on a dry basis. The yields per ton of coal of this general quality are given in Table LVIX.

TABLE LVIII

	COAL	SEMI-CARBOCOAL
Volatile matter	35.3	9.30
Fixed carbon	57.6	80.93
Ash	7.1	9.77
	100.0	100.00

TABLE LIX.—YIELDS PER TON (2,000 LB.) OF COAL, 35 PER CENT VOLATILE CONTENT IN THE PRIMARY DISTILLATION

Products	Units	Gross yield	Salable products, net yield
Semi-carbocoal	Pounds	1,440	1,440
Dry tar	Gallons	24	
Light oils	Gallons	.....	2
Heavier oils	Gallons	.....	13
Pitch	....	.....	9
Ammonium sulphate	Pounds	12	12
Gas, 650–750 B.t.u	Cubic feet	5,000	1,500

It is possible to recover a small yield of ammonium sulphate from the first distillation. In a plant containing only primary ovens, however, this may not pay owing to the present high cost of by-product recovery apparatus. The light oil yield is recovered partly from the distillation of the tar and partly by stripping the gas.

There are several ways by which the process may be used in connection with the generation of power.

1. The Single-stage Process.—(*a*) The size of the installation can be such that it will operate continuously at a load factor of, say, 90 per cent. and supply enough fuel to carry the average summer load. This would only require sufficient storage capacity for semi-carbocoal to take care of the hourly fluctuations in load and a limited amount of daily or monthly fluctuation. The additional winter load could be carried with raw coal.

(*b*) This plant can be enlarged to supply the entire annual fuel requirements of the power plant, and extra storage capacity provided for semi-carbocoal. The distillation plant can operate continuously and the part of the winter load which is in excess of the average annual load can be carried with semi-carbocoal from the storage pile. The size of the power plant would often determine which of these alternatives was most economical.

2. The Complete Process.—(*a*) The installation of primary retorts can have a sufficient capacity to supply semi-carbocoal to carry the maximum daily winter load with sufficient storage to take care of hourly and daily fluctuations and sudden peak load demands. This installation would operate continuously throughout the year, and the surplus semi-carbocoal would be made into carbocoal briquets and sold for domestic and other uses. A part of those made in the summer would be stored for the winter use of the distributors and consumers.

(*b*) Where the markets for semi-carbocoal and for carbocoal are sufficiently large, the carbocoal plant can have a capacity in excess of the maximum demand of the power plant.

3. By-product Gas Producer.—Instead of burning semi-carbocoal under the boilers, it may be burned in by-product gas producers, and the gas can be treated by the Lymn process for the recovery of ammonium sulphate. The combination of these two processes is discussed under another heading on page 353.

ESTIMATED RECEIPTS PER NET TON OF COAL CARBONIZED

Table LX.—Making Semi-carbocoal

	Plant *A*, at a distance from mines, coal @ $6.22 per ton		Plant *B*, at mines, coal at $2.90 per ton	
1,400 lb. semi-carbocoal.	@ $6.22	$4.35	@ $2.90	$2.03
2 gal. light oil.....................	@ 0.20	0.40	@ 0.18	0.36
13 gal. distillates..................	@ 0.25	3.25	@ 0.23	2.99
9 gal. pitch.........................	@ 0.07	0.56	@ 0.05	0.45
1,500 cu. ft. surplus gas............	@ 0.30	0.45	@ 0.15	0.22
12 lb. ammonium sulphate	@ 0.016 (net)	0.19	@ 0.016	0.19
Gross receipts......................		$9.20		$6.24
Cost of coal........................		6.22		2.90
Net receipts........................		$2.98		$3.34
Net receipts with coal and semi-carbocoal......................			@ 2.15	$3.56

Table LXI.—Making Carbocoal and Semi-carbocoal

	Per cent of output of plant	Plant *A*, coal at $6.22 per ton, carbocoal at $10.40		Plant *B*, coal at $2.90 per ton, carbocoal at $7.08	
980 lb. semi-carbocoal....	70	@ $ 6.22	$ 3.05	@$2.90	$1.42
420 lb. carbocoal........	30	@ 10.40	2.18	@ 7.08	1.49
3 gal. light oils..........		@ 0.20	0.60	@ 0.18	0.54
14 gal. distillates........		@ 0.25	3.50	@ 0.23	3.22
1,800 cu. ft. surplus gas..		@ 0.30	0.54	@ 0.15	0.27
11 lb. ammonium sulphate		@ 0.016 (net)	0.18	@ 0.16	0.18
Gross receipts...........			$10.05		$7.12
Cost of coal............			6.22		2.90
Net receipts............			$3.83		$4.22
Net receipts with coal and semi-carbocoal........				@ 2.15	$4.58

ESTIMATED RECEIPTS

1. The Single-stage Process.—Table LX contains a summary of the estimated receipts per net ton of coal carbonized in the primary ovens. These figures are based on the yield of products summarized in Table LIX. The prices for the products are considered conservative and semi-carbocoal is assigned a value equivalent to that of the raw coal, in order to consolidate the items of profit and cost of treatment. As present costs of construction and operation may change considerably within a few years, they are not given.

We shall assume carbocoal plant *A* to be located near a large center of population, and at a distance from the mines of western Pennsylvania, where coal of about 35 per cent volatile content is available at a cost of $6.22 per ton. Semi-carbocoal will be sold to power plants and to steam-heating plants in the vicinity. The surplus gas will be sold to the local gas company for distribution and the price of 30 cts. per 1,000 cu. ft. is a conservative value for the sale of coke oven gas, at the plant, under new contracts.

Plant *B* will be located near the mines, where similar coal is available at $2.90 per ton. In order to make this case comparable with Plant *A*, it is assumed that the oils will be marketed in district *A*, at a distance from the mines, and the prices are reduced to allow for a freight charge of 2 cts. per gallon. A reduction is also made in the price of the gas, owing to the lower cost of fuel in the district. In some localities, also, there may not be a market for the gas for high uses and it will be necessary to use some of it for firing boilers, or other low uses, in competition with solid fuel, or to pipe it to a distant market. The net returns are also figured on the basis of coal costing $2.15 at the mine, in order to allow for the possibility of contracting for coal at a lower price, owing to the regularity with which cars can be returned to the mine from a nearby plant. This will allow of steady employment for the miners (see pages 512 and 513). Cheaper coal will increase the net returns of Plant *A* by a similar amount, when the semi-carbocoal is used locally in each case.

2. The Two-stage Process.—Table LXI contains a summary of the estimated receipts from the combined process, with plants *A* and *B* located as in plan (1). The seasonal load factor of the power station will be taken at 70 per cent—disregarding hourly, daily and weekly fluctuations. Semi-carbocoal will be produced continuously throughout the year and 70 per cent of the annual output will be used for power-plant fuel. The surplus semi-carbocoal produced during the warmer months will be briquetted to make carbocoal. The latter, being a denser fuel, is more suitable for shipment to distant markets or for storage.

In the case of plant *A*, which will be located at a distance from the mines, carbocoal will be sold for domestic fuel in competition with anthracite at $10.40 per ton, wholesale, while at plant *B*, near the mines, it will be sold for $7.08. The difference between these figures represents a freight rate of $3.32, which is the same as allowed on the raw bituminous coal for Plant *A*. This is the current freight rate (plus 3 per cent war tax) on bituminous coal from points in Clearfield and Jefferson Counties, Pa., to Schenectady, N. Y., and is taken as a representative rate for centers of population at a corresponding radius to the east of the mines. The price of $10.40 for carbocoal is taken as a representative wholesale price, corresponding to a retail price of about $14 for stove-size anthracite. This is the current price at Schenectady and the retail price in New York City is somewhat higher, owing to the greater cost of handling and delivery.

The returns from ammonium sulphate are figured on a net basis, deducting the cost of the sulphuric acid required, as explained in detail on page 353. The net receipts, therefore, have been so estimated as to write off the cost of the principal raw materials, coal and sulphuric acid. The power supply for operating the coal-distillation plant will, naturally, be obtained from the main power station and this will represent a small percentage of the semi-carbocoal produced. Table LVIII shows a volatile reduction of 26 per cent, which represents a recovery of 74 per cent of semi-carbocoal, and this is recorded in Table LIX as 1,440 lb. per ton of coal. Tables LX and LXI, however, are based on a recovery of 70 per cent of semi-carbocoal per ton of raw coal and the extra consumption for generating power for plant use should utilize the difference. The net receipts, therefore, must cover the cost of operation, including fixed charges and maintenance, as well as profit.

When operating a power plant with semi-carbocoal, made in a coal-distillation plant under the same ownership, the main product will be electric power, and the item of profit may be credited against the cost of fuel. If the plants are under separate ownership, the semi-carbocoal will be one of the main products of the distillation plant and may be sold at a sufficient differential, below the market price of raw coal, to displace the latter fuel on a large scale. If used in pulverized form, it may be advantageous to combine the milling plant with the distillation plant, thereby concentrating all the preparation under one management. Methods for transporting pulverized fuel through pipe lines for limited distances are available.* The relative advantages of locating plants near the mines, or near the markets for the products, are discussed elsewhere (pages at end of this Chapter).

PLANT AT CLINCHFIELD, VA.†

The first commercial plant for the low-temperature distillation of coal was put in operation in the summer of 1920. This is a complete carbocoal plant and is located at Clinchfield Station, Russel County, Va., at a junction of the Norfolk & Western Railroad and the Carolina, Clinchfield & Ohio Railroad. This point is about 50 miles northwest of Bristol, Tenn., and is located in the midst of an important coal-mining region. Also, it is centrally located with respect to extensive markets for domestic fuel in the Southern States as well as in Ohio, Indiana and eastern Illinois. This plant was started in the summer of 1918, when the United States Government, then very greatly concerned about the supply of toluol and other needed by-products of coal for the prosecution of the war, arranged for its construction. Although the foundation had hardly been cleared when the armistice was signed, yet, recognizing the great need for a plant that would have a potential value, both in times of peace and war, the work was not interrupted when much of the other work tending to increase munition supplies was halted. This plant will be operated by the Clinchfield Carbocoal Corporation by special arrangement with the United States Government, which will, of course, have first call at all times upon its products.

Coal used at this plant will come from the well known Clinch Valley section, the important mines of the Clinchfield Coal Corporation being nearby. The coals in this section, running around 32 to 36 volatile, lend themselves most admirably to the carbocoal process.

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* See Chap. VIII, p. 559.

† Largely from "Artificial Anthracite Manufactured from Bituminous Coal," by M. M. Brandegee, *Manufacturers Record*, July 29, 1920.

The plant is designed to have a capacity of 600 tons per day and is arranged for future expansion, by the building of additional units, to an ultimate daily capacity of 5,000 tons of coal. Figure 97 is a view of the plant taken during construction. Figure

Fig. 97.—General view of the carbocoal plant of the Clinchfield Carbocoal Corporation, South Clinchfield, Va.

Fig. 98.—Primary retorts in the carbocoal plant of the Clinchfield Carbocoal Corporation, South Clinchfield, Va.

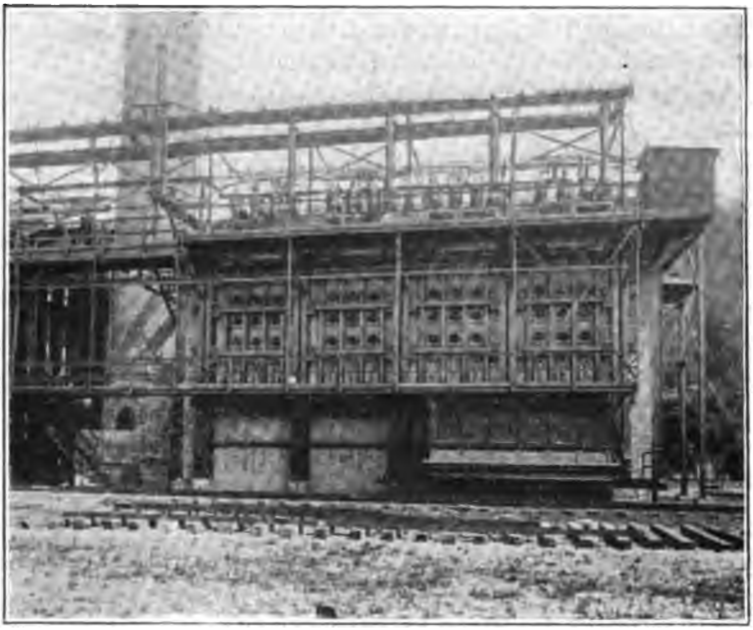

FIG. 99.—Battery of secondary retorts in the carbocoal plant of the Clinchfield Carbocoal Corporation, South Clinchfield, Va.

FIG. 100.—General view of by-product plant, Clinchfield Carbocoal Corporation, South Clinchfield, Va.

98 shows the bank of primary retorts and Fig. 99 the secondary retorts. Figure 100 illustrates the by-product plant with the benzol-scrubbing towers in the background.

The plant is located on a tract of land, 20 acres in extent, which allows room for extensive future expansion.

Coal Handling.—Space is provided for a large coal storage, the handling being done by locomotive cranes. Much of the coal, however, will be brought in cars directly from the mines to the coal-crushing plant at the primary retort building.

Here the coal is elevated from a track hopper to a large coal crusher, and again elevated and distributed by conveyors to six 80-ton feed hopper bins located in the two primary retort buildings. The retorts, 24 in number, are built in batteries of six, arranged in two groups of two batteries. Overhead, and between the rows of retorts thus formed, are the 80-ton feed bins, three bins to each building and its 12 retorts.

The Primary Retorts.—The primary retorts consist essentially of two parts, namely, the muffle or carbonizing chamber and the recuperator. They are heated by gas. The muffle is heart-shaped in cross-section, about 5 ft. high and 7 ft. wide and 19 ft. long, through the center of which run two paddle shafts supported at each end by specially designed end plates and bearings. A gas offtake is provided in the end plate over the discharge. The gas burners are controlled from a passageway below, the waste gases passing up through the separate burner flues, joining in common flues which run along each side of the muffle, and finally descending to the recuperators and stack. The recuperators are simply a series of parallel flues. The hot waste gases travel back and forth and down while the air is progressively heated by passing up in its own flues, counter-current to the hot gases, and thence to the burners. Two 150-ft. stacks located between the buildings take care of the waste gases.

The retort is of firebrick construction, except the muffle, the lining for which is a special carborundum refractory. Each retort is 12 ft. wide, 24 ft. high and 19 ft. long. The whole battery is held together by heavy tierods and buckstays. A 50-hp. motor driving two line shafts, fitted with clutches, etc., operates the feed screws and paddle shafts for 12 furnaces.

Briquet Plant and Briquetting.—The semi-coke discharged from the primary retorts falls on covered conveyors which run along the ends of each battery, and is carried to one or more of four large semi-carbocoal bins in the briquetting building. From these it is dropped to two pulverizers and again elevated to paddle or "cross" conveyors. At this point 10 to 12 per cent. of liquid pitch is added. This is pumped from a 10,000-gal. steam-heated kettle located in the basement of the building. The action of the paddles in the conveying trough tends to mix the pitch and semi-carbocoal, but before going to the presses the mass is thoroughly agitated and heated by direct steam in two steam-jacketed "fluxers" or mixer tanks. The mix coming from the latter machine is a pasty mass, and, while still hot, is run directly to the "presses."

The "raw" briquets fall from the presses to a long cooling conveyor, which carries them up to the raw briquet bin at the secondary retorts, or else directly to a revolving screen, which separates the "fines" and returns the latter by a "refuse" conveyor to the briquet-house for further "pressing." The "screened" briquets are now charged into a lorry and thence to the secondary or high temperature retorts.

Secondary Retorts.—The 10 inclined secondary retorts are built in two batteries of six and four. The batteries are separated by a 150-ft. stack, which carries off the waste gases from all 10 retorts. Each retort is really divided into three vertical sections containing two carbonizing chambers, one over the other, thus making in all six such chambers to each retort setting. The chambers are constructed of silica brick. Two charging doors and one discharge door per section are provided. The retorts are roughly 12 ft. wide by 21 ft. long, 26 ft. high at the discharge end and 39 ft. at the charging end. The incline in the chambers is such that by opening the discharge doors the whole charge will slide out. The furnaces are heated by part of the gas recovered during the process, the air being preheated. The burners are controlled from the top of the retorts and burn down through vertical flues along the chamber walls. The waste gases pass through common flues and thence down to the recuperators and stack. For each retort a separate hydraulic main or tar-catch tank is provided, and this is connected by three gas offtakes over the discharge end of the three banks of carbonizing chambers.

About five tons of "raw" briquets are charged from the lorry into a section of two chambers. The distillation or baking requires from 5 to 6 hr. at a temperature of 980°C. At the end of this time, the discharge door is opened and the incandescent briquets of "carbocoal" slide out on to a "quench" car. After cooling at the quenching station, the carbocoal is elevated to a small 25-ton bin for loading, or else run to a storage yard and held for the market.

RECOVERY OF BY-PRODUCTS

Gas.—The rich gas from the primary retorts passes first into scrubber standpipes, through which tar and liquor are circulated, then to collecting mains, and finally through the common 24-in. foul-gas main to a primary condenser and exhauster. The lean gas from the secondary retorts passes into the hydraulic mains, thence to the collecting mains, and finally through a long 20-in. foul-gas main to a separate condenser and exhauster.

The two primary condensers are of the water-tube type, and the gas passing between the tubes is cooled to about 43 to 50°C. Each condenser is 12 ft. in diameter and 24 ft. high, containing 12,000 sq. ft. of cooling surface each.

Three exhausters, with engines, are provided, one to be used as a spare. Each exhauster handles roughly 24 cu. ft. of gas per revolution, and all are located on a platform inside of the exhauster house. In the same building are also a "Feld" washer (vertical type), ammonia concentrating still and various pumps. Just outside of this building there are also located a tar extractor capable of handling 5,000,000 cu. ft. of gas per day; a secondary condenser of the same type and size as the primary coolers, and two benzol scrubbers, each 9 ft. in diameter and 70 ft. high.

The partially cooled primary and secondary gases, after leaving their respective exhausters or gas pumps, are mixed and carried by a 24-in. connection to the tar extractor. Here the gas, passing through a series of perforated plates and subjected also to a liquor spray, loses all its tar, the clean gas going next to a secondary cooler. Leaving the cooler, the gas is now about 21°C. and enters the bottom of the Feld washer, passes up through a fine spray of weak-ammonia liquor or fresh water, losing practically all the ammonia it contains, and thence to the bottom of the first benzol scrubber. Each scrubber is a tall steel shell filled with wooden grids. A heavy oil is sprayed from the top of the towers and falling on the grids trickles down over their surface. The gas passing up through the wet grids in the first scrubber leaves at the top and enters the bottom of the second scrubber, from the top of which it again descends to a catch scrubber. The catch scrubber, by a series of baffle plates, frees the gas from any oil which may be carried over with the gas.

The gas is now free of tar, ammonia and light oil; it still contains sulphur, but is not further purified, passing directly from the catch scrubber to the fuel gas mains supplying the primary and secondary retorts. A 100,000-cu. ft. gasholder acts as a governor and provides for a 45-min. storage in case of emergency.

Tar.—A large part of the tar is condensed in the scrubber standpipes at the primary retorts and in the hydraulic mains at the secondary retorts. It is returned through separate circulating lines to a catch tank located near the primary condensers. The same tank, by means of two dip pipes, receives the tar circulating and condensing in the foul gas mains. Tar draining from the condensers, exhausters and tar extractor runs to a sump and is pumped to 12,000-gal. circulating tank, into which also flows the tar from the catch tank.

After decantation in a series of tanks, the dry tar flows to a pump tank and is periodically pumped to a 50,000-gal. tar storage tank at the tar-distilling plant. Here the tar is preheated in two 9,000-gal. primary stills by means of the hot oil vapors coming from two coal-fired 8,000-gal. stills. The vapors coming from the primary stills and from the vapor-heating coils in them are condensed by four coil condensers and the oils pass through decanters to 10,000-gal. receiving tanks. Besides this equipment, there are two other coal-fired stills, one of 8,000 gal. and the other 6,000 gal. capacity, each with its condenser and decanter.

Each of the coal-fired stills has a separate pitch cooler, into which the hot pitch is run after a distillation. The partially cooled pitch is then blown into a pitch car and taken over to the briquet plant.

The tar distillates are pumped from the receivers to four 25,000-gal. storage tanks.

Ammonia.—The weak ammonia liquor, decanted from the tar, is pumped to a 50,000-gal. storage tank and circulated through the Feld washers, to bring it up to a strength suitable for concentrating. The liquor, now 1 or 2 per cent in strength, passes to the ammonia still. The concentrated ammonia, 18 to 22 per cent in strength, is then blown by compressed air to two 10,000-gal. overhead loading tanks.

Light-oil Plant.—In the light-oil building is a complete "stripping" still with its preheaters, and a 7,000-gal. crude light-oil still, with short rectifying column and dephlegmator and other auxiliary apparatus, such as the decanters and condensers, oil receiving tanks and pumps. In a small addition to the main building is a 750-gal. light-oil washer, an acid egg, caustic-soda dissolver and a 10,000-gal. washed-oil storage tank. Ample oil storage is provided by eight 20,000-gal. tanks, also a residue tank for the crude still.

The light oil is recovered in the usual way by circulating a heavy oil through the benzol scrubbers, pumping the now benzolized oil through preheaters into the stripping still, where it is subjected to live steam. The hot debenzolized oil from the still runs through heat interchangers to a decanter, and is then pumped to cooling coils and back to the scrubbers. The process is continuous. The light oil from the stripping still is run to a decanter and thence to storage. The light oil recovered from the distillation of the tar, along with that obtained by stripping the gas, is then charged into the crude still and roughly fractionated. It is then pumped to the washer, where it is treated with sulphuric acid and caustic soda, and again charged into the still and fractionated for motor spirits.

Auxiliary Plants and Buildings.—Gas for starting up the retorts and for emergency is furnished by two sets of water-gas generators. A 900-hp. boiler plant with emergency power-generating unit, a large spray pond, a water-pumping station, a completely equipped laboratory, a large machine shop and storage houses complete the plant.

The town is built on a hillside overlooking and adjacent to the plant. It consists of the general-office buildings, stores, bunkhouses, about 20 modern bungalows, manager's house, firehouse, garages, mess hall, clubhouse and other buildings.

THE GREENE-LAUCKS PROCESS*

The Denver Coal By-Products Co. has been carrying on a comprehensive series of experiments in the distillation of bituminous coals at low temperature on a commercial scale. Coals have been obtained in carload lots from several of the Rocky Mountain and Central States, while small samples from many

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* *Coal Age*, May 1, **1919**; *Gas Age*, June 2, **1919**.

localities have been tried out in the laboratory. The inventors of the process are F. C. Greene and I. F. Laucks.

It has been known for some time that the distillation of coal at low temperature will produce a high yield of valuable oils and a coke with superior burning qualities, as compared with high-temperature coke. Low temperatures, however, necessitated a very thin layer of coal in a retort, since heat penetrates a stationary mass of coal much more slowly than at higher temperatures. This renders the types of ovens used for making coke too large and expensive for low-temperature distillation.

FIG. 101.—Experimental plant of the Denver Coal By-products Company.

The Retorts.—In this process the above limitations have been overcome by subjecting a moving stream of coal to continuous distillation in vertical cylindrical iron retorts at temperatures below 600°C. and under considerable vacuum. The retorts used in the experimental plant at Denver, Colo., up to this time have been of 12 in. internal diameter and 18 ft. long. They have usually been made from commercial sizes of iron pipe, both cast and wrought iron. They are heated by retort gas fired under pressure, approximately 1,000 cu. ft. of gas being burned per ton of coal retorted. The burners have a large number of flame jets, which play tangentially against the surrounding firebrick furnace wall, most of the heating being effected by radiation.

Coal, of slack sizes, is fed continuously into the bottom of the retort, where it is propelled upward through the heat zones of internal and external application to the top of the retort, where it is discharged as a well consolidated coke of about 12 per cent volatile content. The propelling agent is a peculiarly devised screw, which constantly turns the stream of coal over and over, resulting in maximum heat application, and maximum opportunity for the vapors to leave the coal mass.

The vapors (the retort making very little fixed gas) are educted at the top of retort into a main, in which a variable degree of absolute pressure is maintained. Methods of conserving heat are used which permit of best operation. Very moist coals must be predried to secure maximum efficiency of the apparatus.

The usual methods are employed for condensing the vapors. A retort of this type has been in continuous operation during the greater part of 6 months up to August, 1921, frequently at a temperature of 1,000°C., and has shown no great amount of depreciation. It is believed that cast iron will show the least depreciation. The process has been developed from small retorts to the present model operating in Denver which has a daily capacity of about 10 tons of coal per unit. One difficulty after another has been overcome in the course of development until all have been surmounted and the process is now considered ready for commercial use.

The screw which propels the coal through the retort is a very essential feature of the process. Probably this is one of the first things that anyone would think of in attempting to make a continuous retort. A search through the patent files will reveal a number of retorts containing a screw as a propelling agent. These inventors, however, failed to recognize the factors which are essential to the successful operation of a screw in a substance like coal, and the difficulties which they encountered were similar to those encountered in the early years of the development of this process. The method of overcoming these is essential to the successful operation of a screw type of retort, and this is the key to the patent protection in this process.

On studying the actions which take place in the retort, it will be found that a screw is the ideal mechanism for producing the desired results. It is essential that the coal be subjected to uniform temperature on all sides during distillation. It is also essential that it be subjected to a certain pressure during carbonization, in order that the semi-coke product may have the required degree of strength. This is admirably accomplished by the type of screw employed.

There is never more than 250 lb. of coal in a retort at any one time. The time of passage through the retort varies with different coals, but may be said not to exceed about ½ hr. There are four factors which are adjustable: (1) the time under heat, (2) the degree of heat, (3) the amount of vacuum, and (4) the degree or pressure. These may be varied to give the best results depending upon the kind of coal used and the character of the coke produced.

The use of vacuum enables the devolatilization of the coal to be affected more rapidly than would be the case at atmospheric pressure, thus increasing the capacity of a given size of retort. The use of vacuum also permits the devolatilizaton of coal at a lower temperature. This allows the use of metal retorts which have a long life. The labor cost is very low, because the process is continuous.

Denver Experimental Plant.—One of the retorts is shown in Fig. 102, which is an oblique front view showing the full length of the cylinder covered with white heat insulation. The most prominent feature in the illustration (in the center foreground) is the discharge tank with Nordstrom-Merco plug valves at the top and bottom. The smaller white cylinder, in the right foreground, is a dust catcher and to the right of this is the heavy oil condenser. The condensers for the middle and lighter oils are located still futher to the right and are not shown.

The screw is driven by the gearing at the bottom of the retort (in the background of Fig. 102), which is more clearly shown in Fig. 103. The motor is located on the upper floor and is belted to a Reeves variable speed mechanism, as shown in Fig. 104. The worm gearing on the floor is driven from the Reeves pulley by the inclined belt shown in the foreground, in Fig. 103 and in the background in Fig. 102. The speed of the rotor is controlled by the chain which hangs from the Reeves pulley (at the right) in Fig. 103. The control instruments are also shown mounted on the wall at the right in Fig. 103. The top of the rotor is shown protruding above the head in Fig. 104.

In the upper left corner of Fig. 104 the top of a coal elevator

Fig. 102.—Experimental Greene-Laucks retort at Denver, Colo.

Fig. 103.—Experimental Greene-Laucks retort at Denver, Colo.

is shown where it discharges the raw coal into the feed vacuum tank on the upper floor (at left). From this the raw coal feeds down throught the inclined pipe, shown at the left in Fig. 103, to the feed screw at the back of the retort.

The coke is discharged from the enlarged head at the top of the retort (Fig. 104) and slides down through the large inclined pipe at the right to the valve on top of the discharge tank (Fig. 102).

The retort is fired by the gas burners shown in Figs. 103 and 104, while the air for combustion is supplied by a fan on the upper floor (Fig. 104) belted to the Reeves mechanism. The gas and air pipes are shown in all three illustrations, while the flue is shown at the top of the retort in Fig. 102.

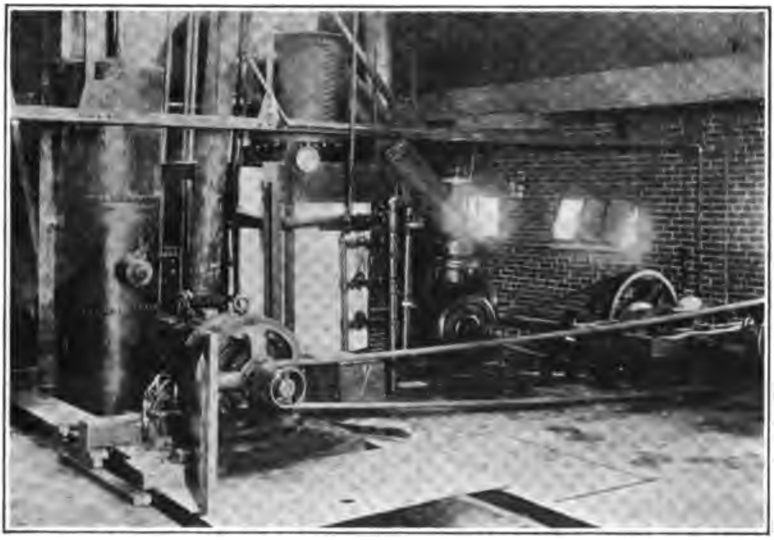

Fig. 104.—Experimental Greene-Laucks retort at Denver, Colo.

The Semi-coke.—The coke produced will run from 1,300 to 1,500 lb. per ton. An important feature of the process is its ability to produce any type of fuel by progressive devolatilization of the coal, such as: (1) a high volatile domestic fuel, (2) a high volatile stoker fuel, and (3) a lower volatile smelter coke. In carbonizing fuel for domestic use and for generating steam, a little less than 15 per cent of volatile matter is left in the coke. It has been found that this makes a fuel which burns much better than a coke of lower volatile content. Also, the oils yielded during further devolatilization of the coke are of low commercial value. It is better, therefore, to leave this volatile matter in the coke. For domestic purposes the semi-coke has been found equivalent to the best anthracite. The cellular structure and strength of the coke are very largely effected by the manner of retorting and are thus under control. It has been found that coke with fairly open structure, but still sufficient strength to withstand handling, gives the best results for domestic use and for steam purposes.

The coke is remarkable for the readiness with which it responds to draft regulation. For example: A bed of the coke in an ordinary stove may be left for 24 hr. or more with the draft shut off. Within a very few minutes after opening the draft, the whole bed can be made red hot. In an ordinary kitchen range 10 lb. will cook three meals and last over night for replenishment the next morning. It is also remarkable for the ease with which it ignites. Very little kindling is required; in fact, a fire can be started with rolled-up newspapers. Apparently the vacuum influences the character of the coke to a considerable extent, as coke made from the same coal at the same temperature, and with practically the same amount of volatile matter left in it, but made at atmospheric pressure, will have considerably different properties than the vacuum coke. Fuel of this kind is somewhat lighter than anthracite and, when made from western coal, burns to a fine powdery white ash without the least suggestion of clinkering. For domestic purposes it has been found to be comparable with the best anthracite, containing 10 per cent of volatile matter.

For domestic uses the fuel would be made quite dense with diminished cell space; for stoker use, where draft can be closely regulated, the density would be made only sufficient to secure the necessary strength to avoid too many "breeze" sizes, and the available combustion surface would be increased to the utmost. Under such manipulation, the fuel has great avidity for oxygen and modern 200 to 300 per cent boiler-load requirements are readily met. In fact, the limit of heat absorption of the boiler and the refractories of the furnace will determine what degree of forcing of the fuel bed is possible.

Apparently, about 15 per cent of volatile left in the residual fuel permits the hardest driving of the fuel bed, at which time also the radiants are at a maximum and the smokeless flame is long enough to reach the furthest passes of the boiler furnace.

When used as a boiler fuel, a free draft through the fuel bed is assumed, since the products of combustion do not exude. Combustion is always complete, leaving no unburned carbon in the ash. A raw coal, containing 30 per cent of ash, when burned on boiler grates had to be sliced half hourly. The same coal carbonized contained 40 per cent of ash and would not slag or clinker when the temperature was sufficient to melt firebrick. The ash bed remains open, the ash partaking of the porous structure of the fuel. Standbys of very long duration can be made by stopping the draft. A full fire can be raised from a cold bed by a few minutes draft. Removal of the ash is facilitated by porosity, which permits of easy wetting for conveyor or blast disposal. No sooting of the boiler tubes or passes takes place.

A prominent feature of the process is the facility with which very lean coals may be manipulated in their intumescing stage, with resulting wide range of density, available combustion surface and hardness of the residual coke.

The Tar Oils and Ammonia.—The oils produced vary greatly with the kind of coal used. For the average bituminous coal with 35 per cent volatile content, 30 gal. of oil per ton is a fair average yield, although the yield from such coal ranges from 20 to 45 gal. per ton in extreme cases. The yields from lignites range from 10 to 25 gal. per ton. With cannel coals, or the canneloid varieties of bituminous coal or lignite, the yields will run very much higher. The oils are characterized by their low content of pitch and free carbon and by a high content of light oils. The pitch content, on redistilling, will not run over 25 per cent—sometimes as low as 10 per cent—five per cent of free carbon is a high figure, and a good part of this is not true free carbon, but fine coal dust. Ten per cent of oil distilling below 170°C. is a fair average. The oils are characterized by a high phenol content. Those distilling below 350°C. will average between 25 and 30 per cent of tar acids. The fractions between 170 and 250° will contain 30 to 35 per cent and with some coals as high as 50 per cent. The total phenol content of the oils consists of about 20 per cent of carbolic acid, nearly 30 per cent of the three cresylic acids, and about 50 per cent of phenols of a higher boiling point than cresylic acids, boiling from 210 up to 400°C. Aside from the phenols, the oils contain aromatic bases, such as pyridine and quinoline, olefines (both the mono- and diolefines), naphthenes and only a small amount of paraffin, except in the higher fractions, which will contain from 10 to 20 per cent of solid paraffins. An important feature of the process is the facility with which the various tar-oil fractions may be influenced in retorting, as to both quantity and quality. The tar-acid content also can be manipulated through a wide range.

Considerable attention has been devoted to working out refining processes for the crude oil produced. It is considered that the oils will be best refined in central refining plants, to which a number of carbonizing plants may be tributary. Taking a yield of 30 gal. of crude oil per ton as a basis, the first semi-crude products average as follows:

1. 4 gal. of crude light oil.
2. 8 gal. of middle oil.
3. 10.5 gal. of heavy oil.
4. 70 lb. of pitch.

1. The light oil can be refined to water-white motor spirit, with a refining loss of 5 to 10 per cent, by the usual refinery methods.

2. The middle oil contains about 30 per cent of tar acids, of which half is cresylic acid. This fraction can be marketed as a flotation oil, crude disinfectant, sheep dip, insecticide, shingle stain, wood preservative, etc. It has been tried in practice in all these uses with good results. This fraction can be further treated to extract the tar acids and cresylic acid, leaving a neutral oil. This neutral oil can be refined by usual methods, and a 10 to 15 per cent refining loss, to make water-white kerosene or burning oil.

3. The heavy oil, as it comes from the first still, is solid at ordinary temperatures, due to paraffin wax. The wax is readily removed by filter-pressing. The pressed oil is a valuable lubricating oil. Considerable attention has been paid to this product. It has higher viscosity and lower cold tests than petroleum oils. Without any special refining, it has no tendency to gum or to emulsify. It has been in use for some time in practical work with excellent results. The pressed wax can be purified to a white wax by the usual methods.

4. The pitch has very different properties than high-temperature coal-tar pitch. It rather resembles asphalt or resins. Special paints have been made from it which have very good properties. The adhesive power of the pitch is great.

It is considered that 20 cts. per gallon for the whole 30 gal., or

$6 per ton of coal, can easily be realized by marketing (1) and (2) direct, and by filter-pressing (3), and redistilling the pressed-out oil. Further refining will increase the gross value of the oils.

The ammonia yield will average about 15 lb. of ammonium sulphate per ton of coal.

The Fixed Gas.—The total gas is usually less than 3,000 cu. ft. per ton of coal. The content of methane is high and, with, a good grade of bituminous coal, the calorific value will be about 750 B.t.u. per cubic foot. A good part of the gas produced is used in heating the retorts, although these can be heated by producer gas if there is a good market for the retort gas. This process produces the volatiles from coal as tar-oils, rather than as fixed gas.

The gas yield may range from 2,000 to 6,000 ft., depending upon the amount of volatile matter left in the coke. When making a semi-coke, with about 15 per cent. volatile content, the yield of 700 B.t.u. gas will range from about 2,000 to 3,000 cu. ft. per ton of coal treated. When making a smelter coke of lower-volatile content, the gas yield may average about 5,000 cu. ft., and, as the residual coke will be more nearly comparable with gas coke, we may make an interesting comparison of the yields of volatile products in high and low temperature processes. According to Table LXII, the volatile products are of

TABLE LXII

GAS AND COKE-WORKS PRACTICE

Gas:
10M @ 550 B.t.u. @ 0.04 lb. per cubic foot = 400 lb.
Tar:
12 gal. (low phenols) @ 9 lb. = 108 lb.
Light oil:
3 gal. (from gas) @ 8 lb. = 24 lb.

Weights of gas, tar and light oil = 532 lb.

GREENE-LAUCKS PROCESS

Gas:
5M @ 700 B.t.u. @ 0.055 lb. per cubic foot = 275 lb.
Tar:
26 gal. (high phenol) = 234 lb.
Light oil:
4 gal. (from tar) = 32 lb

Weights of gas, tar and light oil = 541 lb.

about the same weight in each case. The important difference is that the value of the oil is greater, pound for pound, than the value of the gas.

Table LXIII is a statement of results from carbonizing a very dirty Colorado slack coal, comparable to many low-grade eastern coals. Better-grade eastern coals will give materially greater yields of condensible volatile matter.

TABLE LXIII.—PRODUCTS FROM CARBONIZING A HIGH-ASH COAL

Coal from Walsenburg field (Colorado) with trade-name "Thor" from Huerfano County. The unwashed slack (the material used) having proximate analysis:

Moisture	2 per cent	This very poor coal was used to observe results when using low-grade material.
Volatile matter	28 per cent	
Fixed carbon	40 per cent	
Ash	30 per cent	

Gas analysis (typical after scrubbing); yield, 4,000, cu. ft. per ton.

COMBUSTIBLES		DILUENTS	
CH_4	40 per cent	CO_2	10 per cent
C_2H_6	12 per cent	O_2	2 per cent
Olefines	6 per cent	N_2	8 per cent
H_2	16 per cent		
CO	6 per cent		
	80 per cent		20 per cent

B.t.u. per cubic foot: 793.

Percentage of gas to heat retorts: 50 per cent (=1,600,000 B.t.u. per 2,000 lb. of coal).

Yield of dry tar from Thor coal: 30 gal. minimum per 2,000 lb. of coal.

Analyses of tar:	Light oil up to 170°C	15 per cent	
	Middle oil, 170 to 230°C	30 per cent	
	Heavy oil, 230 to 350°C	40 per cent	
	Pitch, above 350°C	15 per cent	
Middle oil:	Phenols	30 per cent	
	Consisting mainly of carbolic acid, cresols, some xylenols and other phenols.		
Creosote oils:	Tar acids	25 per cent	
Coke: Yield 72 per cent	Moisture (occluded)	2 per cent	
	Volatile	8 per cent	varied at will from 5 per cent to 15 per cent in retorting.
	Fixed carbon	48 per cent	
	Ash	42 per cent	

With 1.3 per cent nitrogen in coal, the yield of ammonia as sulphate was 15 lb. per ton.

Fuel character: strong coke. Burns completely to buff ash. No clinker. This test was made in an older type of retort, in which the raw coal was fed in at the top and the coke discharged from the bottom. The heating temperatures ranged from 100°C. at the top to 600°C. at the bottom.

Other Hydrocarbons.—Materials such as lignite, wood, etc., are readily educted and yield corresponding valuable products. Lignites may be readily formed into strong lumps by a small admixture of bituminous coal. No expensive briquetting is required.

Oil-shale eduction results in a large yield of oils of valuable quality. The capacity of the retorts on shales is 50 per cent greater than on ordinary coal distillation. This process appears promising from the viewpoint of the processing of coal used for generating power. The initial cost as well as the operating cost should be relatively low, and the semi-coke may be burned either direct or in pulverized form, or it may be gasified. The author is indebted to the inventors of the process for information and data.

CARBONIZATION OF LIGNITE

The carbonization of lignite is a subject on which the U. S. Bureau of Mines, the Canadian Department of Mines, and the Saskatchewan government have all done investigation work.*

S. M. Darling† states that the large way to utilize lignite is to carbonize it; that is, break it up into its four main divisions of gas, oils and tars, ammonia, and solid residue, the latter being practically charcoal. The fact that the lignite does not coke in the sense that bituminous coal cokes, but rather crumbles, on being carbonized, makes possible a continuous and comparatively inexpensive carbonizing process. Moreover, lignite parts with its volatile content more readily than does bituminous coal. And it is not necessary to subject the lignite to the high tempera-

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* Consult U. S. Bureau of Mines, *Bull.* **89** by E. J. BABCOCK and *Tech. Paper* **178** by S. M. DARLING, and other publications on lignite.

Also, "The Carbonizing and Briquetting of Lignite," by S. M. DARLING. Published by the Government of the Province of Saskatchewan, Regina, **1915.**

"The Carbonization of Lignites," by E. STANSFIELD and R. E. GILMORE, *Trans. Roy. Soc. Canada*, **11**, 1917 (3), and **12**, 1918.

† "Better Utilization of Subbituminous and Lignite Coals," by S. M. DARLING, Fuel Engineer, U. S. Bureau of Mines. Read before the International Railway Fuel Association, Chicago, May, **1920.** Abstract from *Power*, Aug. 24, **1920**, 313.

ture required to produce commercial coke from coal. The gas is practically all driven off from the coking coal while the charge is still a black, intumescent mass, but it is necessary to carry the temperature several hundred degrees higher to procure a firm, hard coke. This increase in temperature is not necessary or desirable with the lignite. The entire process is mechanical; the fuel need not be handled by manual labor from the time the lignite is loaded into the mine car until the briquets are enroute to the consumer. The costly element of labor is reduced practically to that required for directing mechanical operations.

TABLE LXIV.—THE PRODUCTS OF CARBONIZATION OF LIGNITE

Gas, per ton of lignite, cubic feet	10,000
Oil and tar, gallons	15
Ammoniacal liquor, gallons	65
Carbon residue, pounds	955

LIGNITE GAS *vs.* COAL GAS

	LIGNITE GAS	COAL GAS
Carbon dioxide	15.9	1.34
Illuminants	3.5	4.42
Oxygen	0.2	0.03
Methane	16.1	34.60
Carbon monoxide	19.5	6.75
Hydrogen	43.9	59.19
Nitrogen	0.9	2.67
Candlepower	3.2	16.00
B.t.u. per cubic foot	440.0	630.00

A little more than one-half of the gas is necessary to carry on the carbonizing process; the balance can be used as a city gas for cooking, or for lighting if burned in a mantle, or for furnace fuel, or for generating power by means of a gas engine. Or, if desired, the entire 10,000 cu. ft., can be devoted to these purposes, and the carbonizing carried on with lignite producer gas from a fuel-gas producer.

During the summer of 1921 experiments were conducted with a carbonizing retort at Hebron, North Dakota, under a cooperative agreement between the U. S. Bureau of Mines and the University of North Dakota. A bank of 12 retorts of the inclined type were used and the plan of the work included the carbonization of 1,000 tons of raw lignite by continuous operation, and briquetting the residue into a firm solid fuel. The quantity and quality of the residue, gas and by-products were investigated as well as the operation of the process.

Oil and Tar Products.—Profitable disposition in this country for the oil and tar products remains to be determined. The simple distillation products of the oil can be put to many uses, such as fuel oil for furnaces and internal-combustion engines, gas enriching, flotation and other oils. The use of the light oils as motor fuel is discussed on page 509.

DISTILLATION OF TRENT AMALGAM

Trent amalgam is made by the physical combination of finely pulverized clean coal with various oils, in the average proportion of 70 per cent coal and 30 per cent oil. The distillation of the oil from the coal is mentioned briefly on page 629. When the amalgam is made from petroleum oils and low volatile coals, the temperature used will ordinarily be sufficient to distil only the hydrocarbon oils, about 99 per cent of the oil being recovered, with an increased fraction of light oil.

When the amalgam is made from high-volatile coals, the lighter petroleum oils will distil first; then, as the temperature rises, the tar oils will be distilled from the coal. The amalgam distils at a lower temperature than either the coal or oil when distilled separately. A temperature of 350°C. is sufficient for the distillation of the amalgam to a carbonized residue with a low volatile content. The same coal, when in dry pulverized form, requires a temperature of at least 400° for distillation, while coal which has been crushed to a maximum of ¼ in. may require a 2 hr. treatment at a temperature of from 450 to 500°C.

The light-oil fraction of the distillate is about twice as great as the total yield when the coal and the oil are distilled separately. As pointed out on page 422, the character of the tar oils distilled from the coal at a temperature of 350°C. is probably similar to that distilled at temperatures up to 550°C. The temperature of 350° is probably below the intumescing stage of many coals, where they soften and coalesce into a pasty mass.

The semi-coke can then be recovered in pulverized form, or with the particles only slightly adhering, so that complete regrinding will not be required. This clean semi-coke powder should make an excellent fuel for generating steam and for industrial furnaces where a high volatile coal is unnecessary.

The Trent Process Corporation has been using a small horizontal tubular retort with an internal worm for the experimental work. It is probable that the distillation can be effected by some of the processes already described, although some of those which have been developed for treating raw coal are not suitable for the amalgam.

When making amalgam for distillation at low temperatures, it would probably be desirable to use the less valuable fractions from the tar produced in the process and thus avoid possible dilution of the products with oils of a different type.

One of the principal limitations in connection with the rate of distillation of granular coal is the low thermal conductivity of the mass. This limits the thickness of the mass which can be distilled in the retorts at either high temperatures or low temperatures, and especially in the latter case. The amalgam should have an advantage in this respect, since the continuity of the mass increases the thermal conductivity of the charge in contact with the walls of the retort. This should increase the rate of distillation at temperatures below the intumescing point of the coal, such as are used in this process. This, together with the low temperature at which the amalgam is distilled, should minimize the heat requirements for the distillation process, while effective heat conduction should increase the capacity of the retorts.

Distillation at High Temperatures.—The amalgam has also been distilled at high temperatures in existing types of horizontal gas retorts. In one case the amalgam used for the purpose was made from the same coal as was used regularly in the gas plant where the tests were made, and the tar produced at the plant was used for making the amalgam in place of petroleum oil. A substantially greater yield of gas was obtained per ton of charge than from the distillation of coal alone, and the coke had a greater density.

Amalgam made from anthracite silt and water gas tar also gave an excellent gas yield and made a very good grade of dense coke.

THE UTILIZATION OF THE PRODUCTS OF THE DISTILLATION OF COAL AT LOW TEMPERATURE

This subject has been reviewed to some extent in Chap. V, as well as in the preceding sections of Chap. VII. There are, however, a number of points that require more detailed discussion. These include:

1. The use of solid fuels and gas for domestic heating.
2. The possibilities of the semi-coke as a gas-making fuel, and the utilization of the hydrocarbon gases for enriching water gas.
3. The use of the semi-coke as a steam fuel.
4. The utilization of the tar oils.
5. The storage of fuel for winter use.
6. Economic factors.

Domestic Fuel.—The need for developing processes for carbonizing coal at low temperature, for use in domestic heating, was first recognized in England. The usual method of heating houses in that country is by burning coal in open fires, in the various rooms, cannel coal being a favorite fuel. These coals are rich in resinous hydrocarbons which burn with an attractive flame, but which also generate much smoke. This incomplete combustion of the vapors of the heavier hydrocarbons, together with the loss of much of the sensible heat of the chimney gases, makes this form of heating very inefficient. Cannel coals are non-coking fuels, so far as the older methods are concerned, yet they are rich in by-product possibilities.

William A. Bone, the author of "Coal and Its Scientific Uses," states in the chapter on "Domestic Heating" that:

> "The wastefulness of the Englishman's cheerful fireplace has always been a favorite theme with those iconoclasts who would prohibit it except in their own homes, and if efficiency were the only consideration there is something to be said for its abolition. But with characteristic conservatism, and disrespect for science when it counters his cherished customs, the average Englishman undoubtedly has a decided objection to the introduction of central heating systems into his living rooms and much prefers to be warmed by the radiation from a bright fire."

This is quoted as a generality; but taking the figures of the British Coal Conservation Committee, issued in 1908, that the consumption of household coal in England, Ireland and Scotland was 35,000,000 tons in 1913, we find that 87,000,000 gal. of motor spirits, 218,000,000 gal. of fuel oil, 253,000,000 gal. of heavy oil, 933,000 tons of pitch, and 385,000 tons of sulphate of ammonia, were wasted by burning coal for domestic use without first extracting its by-products.*

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* "Carbocoal Development is Most Timely," *The Black Diamond*, Oct. 25, 1919.

The difference in the efficiency with which a well carbonized fuel may be burned in an open grate, as compared with a cannel coal, is shown by the interesting comparison in Table LXV, which is based on an estimate made in England.*

TABLE LXV

Fuel	Cannel coal	Carbonized fuel
	B.T.U. PER POUND	B.T.U. PER POUND
Heat value in fuel	14,850	13,145
Heat lost up chimney	11,880	5,842
Heat radiated in room	2,970	7,303
Efficiency, per cent	20	55.5

The efficiency estimated for carbonized fuel, when burned in an open fire, corresponds with the average efficiency with which anthracite may be burned in a domestic furnace, according to tests made by the U. S. Bureau of Mines and others. When coke is burned in domestic furnaces, the tests have shown a somewhat higher efficiency, and this will doubtless hold true also for similar types of carbonized fuels. In the case of both furnaces and fireplacesf an appreciable amount of heat is also radiated from the chimney into the house at a low temperature.

Anthracite makes an excellent fuel for open fires, but the large ash content makes the fire dirty to handle. The availability of low ash fuels for carbonizing should largely remove this objection to the open grate fire. The direct radiation of the high-temperature heat into the room is a very desirable feature of the open fire and it can be used to advantage in living rooms to supplement the furnace.

Gas and Solid Fuel.—The same is true of the incandescent types of gas and electric heaters, and of the open wood fire. The latter is very attractive but requires considerable attention, while the gas heater, for continuous service, must be set in a fireplace or have special provision made for carrying away the products of combustion. This is done in connection with the Grinnell system,† in which gas radiators are used in the rooms and the exhaust is piped to a centrally located electric suction fan. The radiators are similar to those used in hot-water

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* Consult also "The Coal Fire" Fuel Research Bcard, Dep't of Scientific and Industrial Research, 16 Old Queen Street, Westminster, London, S. W. J., England.

† Made by the Grinnell Co., Providence, R. I.

systems, but are heated by the passage of the hot products of combustion through the sections.

Some authorities are of the opinion that the most economical and hygienic way to heat a house with a central furnace is to use the latter to maintain all of the rooms at a temperature of not over 62°F. (17°C.) and to depend upon supplementary radiant heat for comfort in the rooms occupied during the day. The radiant heat should be supplied by open fires or incandescent gas or electric heaters.

Where gas is to be used as the main source of heat, the Grinnell system has a considerable advantage over a central furnace, as gas is a more expensive fuel than coal and full advantage should be taken of its being a mobile fuel. Therefore, it should be applied in the rooms where the heat is needed and shut off in unoccupied rooms. Also, the functions of maintaining a base temperature of 62°F. (17°C.) may be combined with the high temperature heat in radiant form from the same source—at least within the limitations of the load factor of the gas supply system.

Where gas is used extensively for heating houses it will probably be necessary to supplement it with solid fuel for carrying the peak loads during the periods of coldest weather. The most desirable way to do this should be by burning carbonized fuel in open fires and in stoves, according to convenience. This applies to peak loads of relatively short duration, as for a week or two.

Where a better load factor is necessary, before the gas company can give attractive rates, furnaces can be used during the colder months and carbonized fuels burned in districts remote from the anthracite fields. They can also be used to supplement the anthracite supply in other districts.

The inconvenience of the frequent rekindling of open fires or furnaces, when used intermittently to supplement gas, may be overcome by the use of a gas torch for kindling purposes. The author has used one for kindling furnace fires when burning either anthracite, coke or carbocoal. It was made in the form of a bunsen burner, with a blast-tube of 1-in. iron pipe, 20 in. long. The mixer was a standard device and the consumption was 2 cu. ft. per minute. The time required for kindling a furnace fire is 20 or 30 min.

While gas may supersede solid fuels for domestic heating in cities and towns to a limited extent, it can hardly be expected to be a complete substitute owing to the poor load factor encountered in this service. There will always be a field for solid fuel for carrying the peak loads in cold periods; also, the houses in country districts must remain dependent upon solid fuel.

One of the most important aspects of the use of gas and carbonized fuel for domestic heating is their substitution for bituminous coal in cities where anthracite is too expensive, and the consequent elimination of smoke. The elimination of the damage caused by smoke is of sufficient importance by itself to make this change worth while.

Gas From Distillation Processes.—Processes for the distillation of coal at low temperature are not primarily gas-making processes, since the limited yield renders the gas a by-product rather than a main product, and, when no other type of gas is available at a low cost, a considerable part of the gas is required for heating the retorts and tar stills. The fact that the gas is relatively rich in methane, however, renders it valuable for enriching water-gas, in place of oil, when the calorific standards are sufficiently low.

The possibilities of these processes for carbonizing coal for making producer gas or blue gas have already been mentioned. They will now be reviewed more in detail.

The Use of Carbonized Fuels in the By-product Gas Producer.—While by-product gas producers have been used to a considerable extent in Europe, where fuel is expensive and non-caking coals have been available, in American the development of this industry has been retarded, until the last year or so (1920), by difficulties arising from the use of caking coals. When these coals are carbonized, such difficulties disappear.

In the high-temperature carbonizing processes used in the gas and coke industries, the ammonia recovered usually represents only 15 to 20 per cent of the original nitrogen in the coal.

According to O. Simmersbach,* the percentage of the original nitrogen remaining in the coke varies inversely with the temperature of carbonization, ranging from nearly 72 per cent in coal carbonized at 600°C., to 50 per cent in coal carbonized at 1,000°C. and about 26 per cent after 1,200°. Tests made by the Power Gas Corporation in England, however, indicate that but little ammonia can be recovered from the cake made at high temperatures when this fuel is burned in by-product gas producers.

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* Consult: "Coal and Its Scientific Uses," by Wm. A. Bone, Longmans, Green & Co., **1918**, 77.

Evidently the original organo-nitrogen compounds are dissociated by the high temperatures used during carbonization, and the nitrogen has been reduced to an inorganic form (see pages 421 and 422) and can be expelled only as elementary nitrogen. Coke breeze, however, contains portions of the charge which have been carbonized at a lower temperature and has a higher nitrogen content than the lump coke from the same ovens. A sample of breeze produced in England, and analyzed by the U. S. Bureau of Mines, showed a nitrogen content of about 1.0 per cent (air dried).* Some experiments have been conducted in England by the Power Gas Corporation and others, with a mixture of raw bituminous coal and coke breeze in by-product producers. At this time no definite results are available, but the reports are that ammonia is being successfully recovered from the breeze in about the same percentages as obtained from coal.

Semi-coke, produced by the distillation of bituminous coals at low temperature, should be an ideal fuel for the by-product producer. The only available record of a test, where semi-coke has been gasified, appears in Parr and Olin's report† on the coking of Illinois coals at low temperature, from which the following extracts are taken.

The fuel used in this test was the semi-coke product obtained in subjecting Vermilion County screenings from the University power plant to low-temperature distillation (400 to 550°C.). This test material consisted of pieces varying in size from ¾ to 2 in. in diameter, but the charge as fired contained some dust. It was light and porous and lay on the fuel bed without showing much tendency to pack. The analysis was as follows:

Table LXVI.—Proximate Analysis of Producer Test Fuel

Moisture	2.28
Ash	15.82
Sulphur	3.13
Volatile matter	18.00
Fixed carbon	63.90
Calorific value (B.t.u.), dry basis	11,601

The producer used was a No. 3 Otto, designed to operate on anthracite pea coal, with a wet scrubber attached. The latter was merely a shell filled with coke, through which the gas, admit-

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* R. H. Fernald, U. S. Bureau of Mines, *Tech. Paper* **123**, p. 13.

† Univ. of Ill., Eng. Exp. Sta., *Bull.* **79**, 1915.

ted at the bottom, passed counter to a stream of water flowing from the top. Using anthracite coal, the normal capacity of the producer was 4,500 cu. ft. of gas per hour.

In place of the gas engine, which, under normal working conditions, draws the gas from the scrubber, a Schütte-Koerting steam ejector was used. This delivered the mixture of steam and gas to a condenser and thence to a Westinghouse meter of the wet type which had been calibrated just before the test was made.

Dimensions and Proportions

Great area, square feet	1.666
Mean diameter of fuel bed, feet	1.545
Depth of fuel bed, feet	2.21
Area of fuel bed, square feet	1.877
Approximate width of air spaces in grate, inches	0.5
Area of air space, square feet	0.722
Ratio of air space to whole grate	0.433
Area of discharge pipe, square feet	0.165
Water heating surface in vaporizer, square feet	2.7

The firing sheet for this test showed that the producer ran successfully and gave little trouble. Because of the small diameter of the fuel bed, resulting in considerable friction, the lightness of the material used, and its slight tendency to coke and arch, the fuel above the bed proper did not feed down as rapidly as it was burned. Hence it was necessary, about once an hour, to poke it down with a slice bar, and in this respect it probably required a little more attention than a charge of anthracite. It may be noted, however, that it was necessary to poke and clean the grates from the bottom but once during the six hours of the trial. With so small a producer this indicates a remarkable freedom from ash and clinker trouble. On cleaning the fire, small pieces of clinker were found in the ash, but there was none at all sticking to the sides, where it usually collects. The high grate efficiency, 98.2 per cent, also shows that the fires required little attention, since poking and cleaning invariably force much unburned carbon out into the ash.

The fact that the fire required so little attention has an added significance in connection with a producer having a small fuel bed, such as the one used in this test. Usually, the inrush of air, when the doors are opened for cleaning, dilutes the gases sufficiently to make them too lean to burn; but with the fuel in question less trouble was experienced in this respect than is usually the case with anthracite, or at no time did the pilot flame go out and there was no great variation in the calorimeter readings.

A study of the temperature of the gas leaving the producer throws considerable light on the condition of the fuel bed. If the bed becomes clinkered, or if holes form in the fire, air goes through without coming into intimate contact with the carbon. This chimney effect causes the gas to burn at the surface of the bed and the temperature to rise. Sometimes it is very difficult to keep the temperature down, and cleaning and poking have little effect. In the case under discussion, however, the temperature never rose above 420°C., except during the last twenty minutes of the test, when the fire was so low that it was essentially a furnace and not a producer.

No trouble was experienced with tar. There was little evidence of its presence in the fuel bed, and an attempt to get a sample of it from the gas leaving the producer showed that it was present in negligible quantities only. On cleaning the ejector at the close of the run, a small amount of tar was noticed, but most of the deposit was of the nature of scale. It is to be remembered that, before going to the ejector, the gas had first passed through the scrubber.

The efficiencies (hot gas, 74.4 per cent; and cold gas, 64.9 per cent) compare very favorably with those obtained in using anthracite of the same ash content.

TABLE LXVII.—FUEL DATA OF PRODUCER TEST

Duration of trial, hours	6.33
Fuel consumption per hour:	
Dry fuel per hour, pounds	58.8
Dry fuel per square foot of grate area per hour, pounds	35.3
Dry fuel per square foot of fuel bed per hour, pounds	31.3
Gas:	
B.t.u. per cubic foot (high value, standard gas at 16.5°C. and 30 in. pressure)	121.0
Volume of standard gas, cubic feet per hour	3,660.0
Volume, per pound of dry fuel	62.3

COMPOSITION OF GAS BY VOLUME

CO_2	4.15 per cent
CO	21.1 per cent
O_2	0.3 per cent
H_2	11.8 per cent
CH_4	1.5 per cent
N_2	61.0 per cent.

The possibilities of semi-carbocoal as a fuel for use in the by-product producer are indicated by the high nitrogen content in the analyses in Table LXVIII This is a non-caking fuel and is practically tar free.

TABLE LXVII

(1) A well known Pittsburgh coal:

	Raw Coal Per Cent	Semi-carbocoal Per Cent	Ratio of Increase in N.
Moisture	1.09	1.87	
Nitrogen	1.52	1.74	1.145
Volatile	31.82	8.57	
Fixed carbon	57.23	76.52	
Ash	9.86	13.04	
Sulphur	1.25	0.83	
(2) Another Pennsylvania coal:			
Nitrogen	1.41	1.65	1.17

The concentration of the nitrogen content in the carbon residue is usually in this proportion. The recovery of 12 lb. of ammonium sulphate in the primary distillation of the carbocoal process represents only about 10 per cent of the available nitrogen in the coal. A combination of the two processes, low temperature distillation and the by-product producer, would recover a maximum yield of tar and ammonia products.

Combination Units.—The combination of these two operations (distillation and gasification) in a single machine has been mentioned on page 428. This is being done in a number of gas producer installations in Germany. Where the distillation gases are kept separate from the producer gas, and the sensible heat of the latter is used to effect the distillation, this should make a very simple type of plant. It should also be efficient insofar as the gasification of the fuel is concerned; and the utilization of the hot coke by this method appears more practical than the conveying and firing of hot semi-coke as boiler fuel—a procedure which has often been suggested.

The gasification of the semi-coke makes possible:

1. The recovery of the nitrogen by-products.
2. The location of the by-product plant and the power plant in separate buildings. The use of gas as boiler fuel will conduce both to cleanliness and convenience in the power station.

Insufficient information is available for a comparison of the merits of the German type of combined gas producer and low temperature retort with the more elaborate processes for carrying out the two operations independently. The possibility of combining the two operations in a rotary producer has been mentioned on page 428, although the dilution of the distillation gases is a disadvantage.

E. Roser* reviews the limitations which differentiate the recovery of tar in the gas producer from those obtaining in the low-temperature retort, as follows:

"In producer-gas plants, the temperatures in the different zones do not remain constant. The producer frequently has to be stoked, unequal size of coal causes rim firing, parts of undistilled coals enter the gasification and even combustion zones, before being distilled or gasified. All these circumstances make it impossible to produce light hydrocarbons in producer-gas plants, even if they are run slow and cold. The great increase in the output of tar at low-distillation temperatures points also to the fact that, when distilling in a gas producer, the yield of tar depends to a great extent on the temperatures prevailing in the distillation zone. The output of tar is much lower when distilling the coal in a gas producer than when treating it in the rotary oven at low temperatures."

Gas for General Distribution.—The successful utilization of semi-coke from low temperature distillation processes, for the manufacture of blue gas, will open new possibilities for the gas industry. Blue gas makes an excellent industrial fuel and can be used more efficiently than producer gas. As the calorific value is more than twice as great, it may be distributed through smaller pipes. It was used as a domestic fuel in Bridgeport, Conn., a number of years ago, being burned in house-heating furnaces. In this case it was made from bituminous coal in a Loomis-Pettibone producer, but by a method which is hardly practicable for general application, as the charge was steamed in alternation with runs for making producer gas for engines. The use of such lean gas for general distribution, however, was too much of an innovation to survive a change in the ownership of the local gas company.

This opens the entire question of the kind of gas which is most desirable for general use, both from the point of view of

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* Ref. cited on page 439.

manufacturing processes and with regard to utilization. The following extracts from recent discourses by prominent engineers cover the economics of the cituation in a forceful manner. The first is from an address by R. S. BcBride, then engineer-chemist of the U. S. Bureau of Standards, delivered before the Cleveland Section of the American Chemical Society,* entitled "Some Principles Underlying Gas and Fuel Supply."

"Gas a Substitute for All Other Fuels.—Several engineers have in recent years been giving a great deal of consideration to the question as to whether or not it will be possible in the future to eliminate solid and liquid fuels from domestic and industrial use in our cities, and so arrange things that all the heat, light, and power required for municipal life can be secured from gas and electricity. A consideration of this possibility affords a splendid picture of what our city fuel supply problem really is. It will be worth while, therefore, to give considerable attention to this question.

"It has been estimated that the ordinary large city of the northern States will require, on the days of maximum need during cold weather, about 18 times as much fuel as is necessary on certain days of minimum demand in the summer. In computing this, it is estimated that all coal, coke, oil, and gas are added together in terms of the total requirement for industrial and domestic service. How to meet such a demand is a serious question.

"We could analyze the city distributing system and the commercial and general office expenses of the city company, and we would find tremendous increases in the cost for service when the demand was irregular. If it were a coke-oven installation, and we demanded 18 times as much gas some days as others, we would probably multiply the cost of production by four or even five, as compared with the cost if we took the gas uniformly throughout the year.

"With water gas we would not find so great a proportional increase, since a larger portion of the cost of water gas is operating expense and the smaller portion capital. However, in this case the original cost would probably be higher than for either natural gas or coke-oven gas, and hence no matter what the variation in demand might be we would find the water gas at a disadvantage in most circumstances if used alone.

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* Reprinted in *Gas Age*, Dec. 15, 1919, 529.

"The above comparisons are purely theoretical ones, as pointed out, but they have a very practical significance. Henry L. Doherty has made a study of some of these questions and has urged that the practical method of meeting our city fuel need is a combination of these various systems of gas supply, taking advantage of the good points of each system so far as possible, and eliminating as completely as can be done the disadvantages of each.

"However, it is clear that the complete elimination of solid fuel would have very great advantages indeed. With such elimination we would do away altogether with the smoke problem of the cities. We would do away with the difficulty of hauling the solid fuel about the city, with consequent dirt and annoyance. We could eliminate, to a large extent, the investment which the customer must make in coal handling and coal storage facilities. Great increase in convenience of fuel use is, of course, always possible where gas is substituted for coal, since the gas heating is so much more readily controlled and with it the labor needed in connection with furnaces is greatly reduced. And so far as by-product gas was used, the recovery of ammonia, tar, and other products would add greatly to our supply of raw materials for our chemical industries.

"All these factors make it very desirable indeed that we consider every possible means for the advancement of the use of gas and the elimination of solid fuel in city activity. In fact, it is hardly too optimistic to say that within a generation we can hope for the condition that all of the heat, light, and power required will reach the consumer through a pipe as gas or over a wire as current. I speak of this, however, not as a thing easily to be realized, but rather as a national problem of great importance demanding consideration and study."

The second excerpt is from an address by Henry L. Doherty, of New York, upon "Vital Issues Affecting the Gas Industry," delivered before the American Gas Association.*

"**Standards of Gas Quality.**—We must have rational standards that fit our present time and not be tied down to the standards which were made in the days when gas was used only for lighting and used in open burners. Such gas as we do sell is now sold for a different purpose and under vastly different conditions. The future of the gas business depends upon substituting gas

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* Reprinted in *Gas Age*, Nov. 15, **1919**, p. 437.

for solid fuel. We need men with the vision of prophets, rather than men who simply know the history of the gas business. The standards under which we now work are absurd, unnecessary and a relic of a by-gone day. I doubt if any gas company today sells more than 4 per cent of its gas for use in open-flame burners, and it is ridiculous to enrich gas with hydrocarbons at great expense, so that 40 ft. out of every thousand can be used in the most wasteful way to produce light.

"The public itself would be benefited if we served a non-limunous gas, for this would force an economical method of using the gas on the part of the unthrifty. After having been a producer of gas for a great many years, I am now a large producer of oil; and if I were to advocate what would best serve my business interests, I of course would advocate high B.t.u. standards and high candlepower standards, just to insure a market for oil, but I hold that both are unnecessary and are generally a waste of good material. I will go further than this and say that I seriously doubt whether the ideal gas will contain any hydrocarbons whatever.

"Here is a question that I would like to interest the gas fraternity in solving. What is the most desirable gas to serve from a customer's standpoint? There is absolutely no reason for fixing on a gas of approximately 600 B.t.u. per cubic foot. There is no elemental gas of such a relation between density and heating value. The only reason for such a standard is because, by our present methods of carbonization, a good quality of gas coal tends to produce a mixture of elemental gases having a value of approximately 600 B.t.u. The consumer is no better off with 1 cu. ft. of a 600-B.t.u. gas than he would be with 2 cu. ft. of a 300-B.t.u. gas, and, given a proper interest in the development of appliances, I am inclined to believe that far better results would be gotten from 300-B.t.u. gas.

"For some reason it always seemed revolutionary to gas men to talk about serving a non-luminous gas and especially to talk about a gas containing no hydrocarbons. I have tried to get away from a standard of illumination and a fixed heating standard for a given unit of volume. Coal gas is now sent out to the mains containing hydrocarbons having considerable value for many other different purposes, and which, to the gas customer, are of no more value than a like amount of non-luminous gas. In making carbureted water gas we must supply in our manufacturing process valuable hydrocarbons that are either not needed at all or else are not needed to the extent required by our present standards.

"**Properties of Gases.**—If we ever develop the gas business to a high degree of efficiency, I am inclined to think that even with room heaters we will find that the greatest efficiency will be secured by the use of recuperators and that practically all of our industrial appliances will be equipped with either recuperators or regenerators. Hydrocarbons are objectionable on account of breaking down during the pre-heating process and depositing carbon in the regenerators or elsewhere.

"I am rather of the opinion at this stage of my investigation that the most satisfactory gas of any that we now have would be a blue water-gas except for its large content of carbon monoxide. I am quite sure, however, that a gas running largely hydrogen would prove a very satisfactory gas and a much more satisfactory gas than the public now gets. There seems to be a universal belief that the quality of the gas is fixed by what I might term its B.t.u. density. or, stating it in other words, that gas having the greatest number of B.t.u. per cubic foot is the best gas! That is far from true.

"Methane, having about 1,000 B.t.u. per dubic foot, has a much lower flame temperature than either hydrogen or carbon monoxide, although these gases run in the neighborhood of 300 B.t.u. per cubic foot. Methane also has such a low rate of flame propagation that it cannot be used for some purposes. For instance, methane cannot be used in a blow-pipe. If we take 16 lb. of methane containing 4 lb. of hydrogen and 12 lb. of carbon, it would only produce in combustion about 90 per cent as many B.t.u. as if we were to burn 4 lb. of hydrogen gas and 12 lb. of solid carbon. The less amount of heat by the burning of the methane is due to the heat required to dissociate the CH_4 molecule.

"**Motor Fuels.**—The only place where methane is more desirable than, for instance, a blue water gas, is for use in an internal combustion engine where the Otto or some similar cycle is used, and the gas and air are mixed with each other during the compression stroke. Methane permits of a very heavy compression, while the gas containing a large amount of hydrogen will prematurely ignite at heavy compression. At the time of the threatened shortage of motor fuel and when France and England were offering huge rewards to anybody who would find a substitute for gasoline, I proposed to the motor industry of these countries that they advocate the removal of the light oils from town gas and use them as motor fuel. This was in 1911.

"In 1913, at the request of people interested in the automobile industry, I started a campaign in England which was intended to secure the necessary legislation to permit this to be done. At that time, if all the gas sold in Great Britain had been manufactured from coal and all the light oils had been extracted for motor fuel, Great Britain would not have been compelled to import a single gallon of gasoline.

"I also showed how vehicles like buses with a fixed route could use town gas instead of gasoline by having stations along the route where gas could be charged to the vehicle under pressure.

"My campaign was very favorably received almost everywhere, except by the gas men themselves and the people they could stir up to oppose it, and much of the opposition took the form of ridicule and statements which were not true. War necessity demonstrated the possibilities and the correctness of the picture I then drew.

"**Rate for Gas.**—In the earlier days of the gas business we saw a number of attempts made to furnish fuel gas. In some instances these attempts were made by men who knew neither their chemistry, their physics nor their economics. No matter how efficient our gas-making processes may become, and no matter how inexpensive the necessary manufacturing apparatus may become, it will never be possible to substitute gas generally for solid fuel and sell gas at a fixed price per thousand cubic feet. Some gas consumers would lose money for you at $10.00 per thousand cubic feet, while other gas consumers might yield you a handsome profit at 50 cts. a thousand cubic feet.

"Our expenses are not in proportion to the amount of gas consumed. Our expenses are fixed by the number of customers we serve and by the maximum rate of demand made by these customers. I have never seen the slightest reason to change from the opinions I have expressed in our old gas conventions regarding the correct method of selling gas. I think we must adopt the 'readiness-to-serve' method and apply it universally to all consumers.

"**A Customer-demand Gas Charge.**—The interests I represent are proposing now to serve the customers on the line of the Kansas

Natural Gas Company, the Wichita Natural Gas Company and the Quapaw Gas Company with gas at these rates for natural gas:

"An annual customer's charge of $6 plus

"An annual demand charge of $0.32 per cubic feet per hour plus

"A gas charge of $0.30 per 1,000 cu. ft.

"The customer can contract for whatever demand he wishes to use, and is to be limited to this demand by an automatic device which we have developed. That is, if the customer pays for a 50-ft. demand, his meter will be equipped with a demand regulator, and that will only permit 50 ft. to pass. For instance, under the new method of charging, a customer using 150,000 ft. of gas for cooking and heating his home and requiring a demand of 100 cu. ft. per hour would pay,

Customer's charge	$ 6.00
Demand charge	32.00
Gas charge (150,000 ft. at 30 cts.)	45.00
Total	$83.00

making an average cost of gas to him of 55.3 cts.

"We propose to supplement natural with artificial gas as the natural gas fails, and we have agreed to sell this gas on a basis of

"An annual customer's charge of $6 plus

"An annual demand charge of $0.50 per cubic foot plus

"A gas charge of $0.40 per 1,000 cu. ft.

"In this case a cubic foot of gas shall be 1,000 B.t.u.; or, in the event that 500 B.t.u. gas is supplied, then the company will have to supply 2 cu. ft. to count as 1 cu. ft. To avoid the complication of talking cubic feet and thousands or millions of B.t.u., I suggest the adoption of 1,000 B.t.u., to be known as a "gas unit," and then we can use this term to express whatever quantities of gas of varying calorific value and mean the same thing. The price on the artificial gas, in the proposition outlined above, is based on coal at $3 per ton, and is to be advanced or lowered according to the cost of fuel.*

* "A complete bibliography on the rate question will be found beginning on page 380, I, *Am. Gas Inst. Proc.*, 1906. Anybody wishing to look up my specific views on the rate question can get a paper I read before the National Electric Light Association in May, 1900, at the Chicago Convention entitled, "Equitable, Uniform and Competitive Rates;" and for the reasons why it should be applied to the gas business, they can also get a reprint of my testimony before the Kansas Public Utility Commission, which was printed by the Commission and circulated among the interested parties in Kansas.

"I am convinced that it is entirely possible to substitute gas very generally for solid fuel. Picture in your own mind the magnitude and prosperity of the gas business if this could be done and contrast it with whatever future you see in your own mind for the gas business under present conditions. This is not an idle dream; but even if it were, the gas business would be immensely helped by dreaming some along these lines. To accomplish this, we must be able to get out of our ruts and create our own reforms.

"The third extract is from an article by Norton H. Humphreys."

A 425-B.t.u. Gas Ordered for Great Britain.*—Vicissitudes due to war conditions have led to experiences as to the quality of gas that will secure maximum efficiency combined with economy to the user. Freed from the shackles of statutory restrictions, gas engineers have arrived at results that will have a permanent bearing on the future of the industry, as they tend to show that the procedure with respect to regulations of this character has followed the wrong lines. It has been one gigantic blunder that has cost the consumers some millions sterling and handicapped the progress of the industry by enforcing the supply of an unnecessarily high quality of gas at an unnecessarily high price. All parties interested will be benefitted, as the consumer will get more value for his money, and gas undertakings will have greater facility for extending business, particularly in the promising direction of industrial uses. Based on the wrong assumption that the photometer, and later the calorimeter, will accurately indicate the value received by the consumer, the official testing room has been a red herring across the trail, and the engineer has been called to consider the requirements of the gas examiner, to the exclusion of those of his customers.

The suspension of quality restrictions and of penalties attaching thereto was originated by the urgent need for extraction of toluol and benzol from gas to meet the requirements of military authorities, and it was continued for the very good reason that the restricting and allotment methods adopted by the controller placed many gas works in a position that rendered compliance absolutely impossible. And when the stock of coal is nearly at vanishing point, and supplies uncertain, bad gas is better than no gas at all. During the war the government favored keeping

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* *Gas Age*, Nov. 1, **1919**, 388.

as near as practicable to 500 B.t.u. per cubic foot and instances where the supply has been nearer to 400 are not uncommon. Today, under the throes of a national railway strike, and with war experiences before them the government are not only favoring a 425 unit gas, but declaring an excess of that figure to be an offence against the Defence of the Realm Act.

Freed from the burden of restrictions that have long been suspected of inconsistency as regards the real interests of the consumers, gas engineers have ceased to think about quality as merely a matter of candles or units, and in place of confining attention to a product that would pass the ordeal of the parliamentary standard have considered the best methods of meeting actual requirements. In past times these have been fined for defections representing only a few points per cent as inflicting a serious injustice on the consumers, but now they have discovered that a sweeping reduction of 100 or even 150 B.t.u. can be made without complaint other than from the small and diminishing proportion of flat flame users. There is not a larger number of complaints as to bad supplies or heavy charges, and a marked reduction in those referring to sooty mantles or choked burners. The only question is the extent to which "dry" gas agrees with the flexible diaphragms of dry meters.

Attention to the interests of the user has been confined to the quality as supplied to his meter; whereas the real point is: what does he get out of the gas? Does he utilize its potential value to the full, or does a large proportion go to waste? He pays for, say, 1,000 cu. ft. of gas and the value he gets in return is not necessarily in proportion to the results of the official testings, but turns on the efficiency of the appliances used as indicated both by their design and their state of repair. Another important point that has been brought into prominence is that, in this connection, there is not only the quality of the gas to be considered. Before it can be turned to profitable account it must be mixed with the minimum quantity of air that will ensure complete combustion, which is approximately proportioned to the calorific value. We have to consider, not a bare 600 or 400 B.t.u. gas, but a 600 plus about six times its bulk of air and a 400 plus about four times this volume. The bulk of the gas is used through bunsen burners and it is obvious that with the poorer gas a larger proportion of the total complement can be mixed before combustion. For this and other reasons in practice it is easier to get good efficiency with a poor than with a rich gas, and in the sense that these terms are generally applied they are inappropriate and misleading. If a 600 B.t.u. gas passes through this meter, of which he utilizes only 400, the user is worse off than if he utilizes 420 out of a 480 B. t. u. gas. This is merely a rough indication of the direction in which to look for explanation of the apparent anomaly, that in practice a 450 is as good as a 600 B.t.u. gas, apart from the fact that it can be sold at a cheaper rate.

Since Humphreys' article was written, the old legal standards for gas quality have been superseded in Great Britain and each company is allowed to manufacture gas of such quality as it can produce most economically, with reference to the heat units made available, within certain very liberal limits. The rates in each locality are then based on the calorific value of the gas, which is still sold on a volume basis.*

Mixed Gas from Coal Distillation Products.—The foregoing comments present the situation in the gas industry very clearly. Since they were published, however, the situation has been rendered more acute by the increasing price of the oils used for enriching water-gas. Where gas is supplied in large quantities to a single industry, or group of industries, it would be practicable to use blue gas without enrichment. This, however, would be less practicable in the case of gas for general distribution, and it could not be universally applied owing to the existence of many coal gas and coke oven plants. Moreover, it would leave no outlet for the rich gas produced by the distillation of coal at low temperature, which has a calorific value of about 700 B.t.u. per cubic foot.

The more practical way would be to mix coal gas and blue gas to obtain a product of intermediate richness; or, in other words, to substitute coal gas for oil as an enriching material. Table LXIX gives the calorific values for a few mixtures of gases covering the range of most practical interest.

TABLE LXIX

Volume Ratio		Mixed Gas B.T.U.
700 B.T.U. Gas	300 B.T.U. Gas	
1	1	500
1	2	433
1	3	400
1	5	366
1	7	350

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* Consult "Effects of English B.t.u. Standards," by A. I. PHILLIPS *Gas Age-Record*, Nov. 12, **1921**, 620.

The proportions of the mixture can be varied to suit the availability of plant and raw materials in each locality; but the calorific value of the mixed gas should be held constant within a certain range, to avoid frequent readjustment of customer's appliances.

The outstanding facts are that a sufficient lowering of the present standards of gas quality will open the way to the use of new processes for making gas, as well as the utilization of a wider range of raw materials. When the processes described in this Chapter are developed on a commercial scale, the various gases available for mixing will be:

Lean gases:
- Blue gas made from raw coal, from coke, or from semi-coke.
- Low temperature water gas, rich in hydrogen.
- Gas rich in hydrogen, made by the carbonization of briquets, as in the second distillation in the carbocoal process.
- Producer gas.

Rich gases:
- Gas distilled from coal at high temperature.
- Gas distilled from coal at low temperature.
- Gas made by the complete gasification of pulverized bituminous coal.
- Synthetic methane from blue gas.
- Oil gas, to be used only where oil is cheap.
- Natural gas.

Intermediate gases:
- Gas distilled from low rank fuels and which contain diluent gases.
- Gas made by the complete gasification of pulverized fuels of low rank.

Where gas from coal-distillation processes is used for enriching purposes, provision should be made for heating the retorts with producer gas or blue gas during periods when the demand for gas is sufficiently heavy to require the use of all the coal gas for mixing with the lean gas. During the periods of lighter loads, surplus rich gas may be burned under the retorts or the tar stills. This will allow of maintaining a constant mixture while the coal distillation plant is operated continuously and the blue gas plant can be used to carry the variable load.

The range of variation which may be secured in this way, however, is limited to a ratio of 2:1, or even less, in some processes. As the ratio of city fuel consumption, as between winter and summer days, may reach 18:1, it is plain that the development of a simple process for gasifying pulverized coal, to assist in carrying the peak loads, would be of great value. Even then, the load factor on the gas distribution system presents another economic limitation to the universal substitution of gas for solid fuel in cities. In industrial districts the load factor may be improved to some extent by the substitution of gas for oil or coal for direct industrial heating.

During cold weather the gas can be distributed under pressure and automatic reducing valves may be installed at branch mains and in the consumers' houses. Also, the maximum demand regulator may be used to compel the consumers to supplement their gas supply by burning solid fuel during periods of very cold weather. In northern cities, where coal is now burned in furnaces for 7 months out of 12, the use of the furnace might be cut down to scattered periods aggregating a similar number of weeks. The use of open fires and stoves for supplementing the gas supply, however, would be more desirable and the time of operating the furnace might be further reduced by their use, or even eliminated altogether.

It is hardly practicable to burn gas and solid fuel in the same furnace, and the initial expense of a double installation can be minimized by providing a good gas installation and supplementing this with an inexpensive type of furnace for burning solid fuel, such as the pipeless warm air furnace, or with stoves or open fires. The Grinnell gas room heating system will supplement the more localized heat from the solid fuel fire.

Where the gas is used as an auxiliary fuel under present conditions, the tendency is for the customers to use coal to carry the base load for domestic heating and to use gas to carry the peaks. This is not satisfactory for the gas companies, although the use of gas in the fall and spring months, in place of coal, should help to improve the load factor. Economic considerations demand that the practice be reversed and that gas be used to carry the base load and solid fuel for the peaks. This corresponds with the suggestion made on pages 285 and 286 in regard to the use of gas and pulverized fuels for generating power.

The maintenance of a reasonably uniform demand for gas during the heating season requires the burning of gas during the night and the storage of the heat. The most practical medium for storing heat is the house itself. If well constructed, and provided with double windows, the living rooms and hallways may be kept up to a reasonable temperature during the night and the demand regulator will prevent an undue consumption of gas in the morning to bring up the temperature. At this time an open fire, burning carbonized fuel, can be used to good advantage.

The attractive wood fire may be made very useful for supplementing the gas supply by the addition of a gas torch to overcome the usual objection that it requires constant attention (see page 790). Kerosene lighters are useful for kindling purposes but cannot be used repeatedly, as the stone requires time to cool off. A bunsen gas burner of the ordinary laboratory type, suitably mounted, gives spectacular results when used for kindling a wood fire, or for bringing a smouldering fire to life, owing to the effect of its blast.

This direct combination of gas and solid fuel may offer a practical solution of the problem of carrying the peak loads in domestic heating, as a small amount of gas can be used continuously to maintain the vigorous combustion of a larger amount of solid fuel in a fireplace where the draft is, ordinarily, an uncertain factor. Sir William Siemens, at the time of his death in 1883, was experimenting with a grate which was arranged to burn gas and coke in combination. The fact that little draft is required by some of the carbonized fuels described in this Chapter should render it possible to kindle and maintain open fires with a very small amount of gas.

Compressed Gas.—The load factor, in a plant supplying gas for winter heating, may be improved by the development of other uses for gas in which the maximum demand will occur in the warmer months. The oven gas, from either the high- or low-temperature distillation process, may be compressed and stored in portable cylinders for use as motor fuel, as a substitute for gasoline. Possible applications include motor boats, commercial vehicles for passengers or freight, farm tractors, and stationary engines in country districts where there is no electric service.

Electricity and compressed gas, together, might replace a considerable part of the gasoline required by commercial vehicles. Each would have its own economic field, gas being used for the higher-speed service and longer routes, and electricity for slower speed and local services, especially where many stops are made, as in delivery work. Recharging stations can be maintained for each, where batteries or cylinders can be changed. Gas cylinders for winter use may be charged at night, when the heating load is light, while in summer they may be charged at all hours.*

The Use of Carbonized Fuels for Generating Steam.—Coke breeze and the smaller sizes of gas coke are burned in gas works for generating steam. Usually they are fired by hand and burned on pinhole grates, but the Coxe traveling grate stoker is frequently used for burning breeze. A strong draught is necessary when burning these fuels.

Semi-coke can probably be burned similarly to coke breeze and gas coke, but it has some important advantages. In small boiler plants, such as those used for heating buildings, it should make a good smokeless fuel. When automatic firing is desired. the method used by A. M. Hunt should be of interest. This consisted in firing granulated fuel pneumatically over a grate.

Coke has been burned under boilers in Germany more extensively than in America, and experiences there during the war are of interest.† It was found that gas coke was easier to ignite than metallurgical coke because its structure is less compact. Coke is more difficult to bring to a state of incandescence than coal, but it burns more slowly and keeps the shape of the lump longer. Because it gives off its heat more slowly, and is a more bulky fuel, it is necessary to use a larger grate and a deeper fuel bed.

It has been stated on many occasions that with coke a boiler cannot deliver as much steam as with coal, especially when working at overload. This is due to the unsatisfactory flame formation resulting from the lack of volatile matter. Also, the superheater temperatures are lower, owing to the shorter flame, and to a greater amount of excess air. When burning coke on chain grate stokers, therefore, it was found desirable to gasify a part of the coke in the hopper by making this a gas producer. The hopper was fitted with an inclined grate and a vigorous fire was maintained there. Supplementary air was admitted to the combustion chamber, through pipes which pierced the fire arch, and this allowed the producer gas to burn above the fuel bed. The fire in the hopper also served to ignite the incoming coke.

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* See "Use of Gas as Automobile Fuel," by A. Grebel, Paris, France. Translation from *Le Genie Civil*, describing progress made in Europe; *Gas Age*, May 25, **1920**, 448.

† "Coke Firing" by Reichelt, reprinted in *Mech. Eng.*, August, **1919**, 696.

The limitations of coke as a boiler fuel are clear. Some of these limitations are to be found also in semi-coke, such as greater bulk than coal and lack of caking properties in the finely divided portion of the fuel. The small particles, in some instances, have been found to be so light that they are blown away by a strong draught.

Semi-coke, however, may be made with a considerable amount of residual volatile matter, and this provides a good flame formation. It may be made fairly dense by being subjected to pressure, while in the plastic stage, during distillation in some processes. While, therefore, it should make an excellent steam fuel for small boiler plants in lump form, it will probably be found advantageous to subject it to further preparation, by granulating or pulverizing, before using it in larger plants, as will be discussed in Chap. VIII. The pulverizing of semi-coke will have several important advantages, as compared with burning it in crude form, viz.:

1. The disadvantages which are incident to the bulkiness of the crude material will be circumvented.
2. It can be more readily conveyed, handled, and burned.
3. It can be more efficiently utilized for carrying intermittent loads, such as the peak loads in power systems where the base-load is carried by burning by-product producer gas, which may be made from semi-coke prepared in the same distillation plant.
4. Pulverized semi-coke may be readily stored and kept available for emergency use, without danger from spontaneous ignition. This is an important consideration in reserve steam-power stations used in connection with hydro-electric plants.

Utilization of the Tar Oils.—The tar oils are the most important by-product from the distillation of coal at low temperature, and the tar acids are considered to be valuable constituents, owing to their toxic properties. The properties of these oils, and their various uses, have been quite fully discussed and it only remains to consider the extent of the fields to which they may be applied on a large scale as primary products.

Wood Preservation.—Coal-tar creosote, made from the heavier fractions of the tar, is considered the best preservative for railroad ties, being insoluble in water and non-volatile. Creosote oils obtained from the distillation of low temperature tars are claimed to be considerably better than those obtained from the tars distilled from coal in the ordinary high temperature processes. Some authorities ascribe their superiority as wood preservatives to their high content of tar acids, while others consider that it is due to the oxygenation of the unsaturated hydrocarbons which we present in larger quantity in the low-temperature oils. The oxygenation of the hydrocarbons tends to convert them from liquids to solids, which form a more permanent filler for the cell walls in the wood.

Low temperature creosotes are, therefore, particularly suited for application by the empty-cell processes in which the oil is more economically utilized than is the case when the cells are more completely filled. This may be equally true whether their superiority is due to the toxic properties of the tar acids or to the oxidation of the oil, or to the combined effect of these two factors.

It is customary to use from 6 to 12 lb. of creosote per cubic foot of tie, according to the penetration desired. The lower figure is for the Rüping vacuum process, while the latter figure is for the high pressure process.

The amount of creosote used in treating hard woods and soft woods does not differ materially for the same degree of penetration. Some purchasers of soft yellow pine creosote ties will call for a high penetration, heavy injection, while others treating hard wood ties are satisfied with a light penetration with a corresponding light injection. This is purely a matter of the opinion of the purchaser; if the tie itself is an expensive one, made from a wood which has a greater natural resistance to decay, he may try to save on the amount of creosote injected, while if he purchases a cheap tie he figures that he can afford to spend more money on the preservative. Some authorities prefer the heavy injection in all cases and consider that the protection secured is ample to compensate for the additional expenditure.

Well creosoted ties have, in some instances, lasted from 20 to 30 years, and the mechanical wear becomes the limiting factor in the useful life of ties. The rapid exhaustion of our forests will soon render it necessary to treat all the ties used on the railways in the most thorough way, as well as to use means for protecting them from mechanical wear.

The present annual requirements of the railways of the United States have been estimated as follows:*

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* *American Forestry*, August, **1918**, 675.

West of the Mississippi	50,000,000 ties
East of the Mississippi	80,000,000 ties
Street and industrial railways	20,000,000 ties
Total	150,000,000 ties

A tie measuring 8 ft. by 9 in. by 7 in. contains 3.4 cu. ft. of wood. Using 12 lb. of creosote per cubic foot, each tie will require 5 gal. for deep penetration. The yield of creosote from a ton of Pennsylvanian coal, by the carbocoal process, averages about 9 gal., or enough to treat 1.8 ties. The treatment of 100,000,000 million ties, annually, would require 500,000,000 gal. of creosote, or about four times the present annual consumption of this oil, one-half of which is imported, and would require the distillation of over 55,000,000 tons of coal. This should allow for a substantial reduction in the number of ties replaced, owing to the longer life obtained, as well as for the probable increase in the number of ties in use during the next few years.

As far back as the year 1907, the number of ties which the railroads actually reported having purchased was 154,000,000, while 1915 was a low year. Statistics for 1915, however, are available which show the number of ties treated, and are given in Table LXX.

TABLE LXX.—CROSS TIES PURCHASED AND TREATED IN 1915*

Reported purchased by railroads	97,100,000
Estimated number purchased	121,400,000
Treated with zinc chloride	17,819,284
Treated with creosote	17,077,069
Treated with zinc chloride and creosote	2,182,712
Treated with other preservatives	6,520
Total number treated	37,085,585
Per cent of ties treated	31.2

Cross ties form about 80 per cent.† of all wooden materials which are subjected to preservative treatment. Zinc chloride can only be used in regions of light rainfall, where it is less likely to leach out and be carried off in solution in rain water. A large proportion of the ties treated in the western states is impregnated with zinc chloride.

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* From U. S. Dept. of Agriculture, *Bull.* 549, 1917.

† "Forest Products, Their Manufacture and Use," by N. C. BROWN, p. 293; John Wiley & Sons, 1919.

It is a significant fact that the kinds of timber which are most benefited by preservative treatment are classed among those which have the greatest mechanical value as ties. Untreated cross ties made of hard maple, beech, yellow birch and red birch have a life of only 2 to 4 years; red oak, 3 to 6 years; and white oak, 7 to 11 years. Maple, white oak, red oak and beech stand at the head of a list prepared by the U. S. Forest Products Laboratory, in which timbers are arranged in the order of their mechanical value as ties, being outranked only by black locust which is quite local in its distribution. By treating ties made from these species with creosote, their life can be made comparable with that of any kind of timber available. Moreover, these are common species in the eastern states and some are of relatively quick growth, which is an important factor as regards the future supply of timber suitable for ties.

It has been estimated that approximately 40,000,000 poles are in use to-day for carrying electric wires, of which only 25 per cent. have received some kind of preservative treatment.* Most poles decay at the ground line in from 2 to 5 years. Creosote treatments greatly improve the life of the butts and cross arms. At the present time even our most durable species are being treated with some wood preservative to prolong their service. While railroad ties are generally treated in pressure-tight cylinders, pole butts must usually be treated in open tanks, or with a brush or spray. Hence the penetration secured is less as is also the quantity of creosote required.

Other important applications for creosote are for the treatment of wood paving blocks and farm timbers. The latter include fence posts, shingles and silos,† and structural timber. Some of the pitches and oils should be useful in making paints, varnishes and shingle stains, owing to their marked drying properties.‡ This is evidently due to the oxygenation of unsaturated hydrocarbons. The various applications for wood preservatives are summarized in Table LXXI, which shows the

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* Consult: "Economics of Pole Timber," by E. E. Hartman. *Elec. World*, **72**, 590; "Report of Committee on Preservative Treatment of Poles and Cross arms," N. E. L. A., 34th Convention, **2**, 579 (1911); and also, "Poles and Pole Preservation," by R. A. Griffim, N. E. L. A., 36th Convention, Technical Sessions, 143 (1913).

† Consult: *U. S. Dept. Agr., Farmers' Bull.* **744**, 1910.

‡ See "Utah Coals are now successfully coked," *Gas Age-Record*, Nov. 12, **1921**, 629.

probable reduction in the annual cut of timber which would ensue from a proper treatment of many kinds of lumber. This is based on estimates made in 1909 and the figures for railroad ties are decidedly low by comparison with the figures for annual replacements already given. If no railroad ties were treated, the replacements should amount to about 200,000,000 and the replacements of treated ties should also be doubled.

TABLE LXXI.—ESTIMATED REDUCTION IN ANNUAL CUT WHICH WOULD ENSUE FROM A PROPER PRESERVATIVE TREATMENT OF ALL TIMBER FROM DECAY*

Class	Estimated average life in years		Estimated annual replacements, all species		Estimated saving in annual cut due to treatment, number	Total annual saving, equivalent board measure, 1,000 feet
	Untreated	Treated	Untreated number	Treated number		
Ties	7	17	100,000,000	41,200,000	58,800,000	1,940,000
Poles	13	23¼	2,462,000	1,380,000	1,082,000	64,920
Posts	8	22	500,000,000	180,000,000	320,000,000	1,900,000
Piles	3½	21½	1,140,000	190,000	950,000	159,600
Mine props	3	13	[a]67,000,000	[a]15,300,000	[a]51,700,000	310,200
Shingles	18	32	[b]1,100,000	[b] 625,000	[b] 475,000	475
Lumber	8	20	[c]2,625,000	[c] 1,050,000	[c]1,575,000	1,575,000
Total	....	....	....	....	....	5,950,195

[a] Cubic feet. [b] Feet Board measure [c] Thousand feet board measure.

Present Sources of Creosote.†—Between 90,000,000 and 100,000,000 gal. of creosote oil, valued at nearly $6,000,000, were consumed in the United States in the year 1913 for the impregnation and preservation of wood. Probably half of this consumption was for the treatment of railroad ties, and most of the remainder for paving blocks, piling, and structural timber. Two-thirds of the entire consumption was imported. Coal tar yields 15 to 30 per cent. of creosote oil, according to the kind of tar, grade of oil, and the softness desired in the residual pitch. Water-gas tar yields no creosote, in the strict sense of that term, although the tar is used for creosoting.

Certain heavier fractions of tar, notably anthracene oil, after chemical treatment are successfully used both in this country

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* From U. S. Dept. Agr., *Forest Service Bull* **78**, 1909, p. 27.

† C. G. STORM, "Coal Tar Products," U. S. Bureau of Mines, *Tech. Paper* **89**, 1916.

and abroad for preserving wood, but their use will not relieve to any large degree the urgent demand for creosote. The present serious shortage in the supply can be met only by increase of by-product coking operations and by the immediate establishment of new coal-distillation processes especially adapted to the recovery of by-products.

According to these figures the yield of creosote from coke ovens and gas retorts will average about 2 gal. per ton of coal carbonized. The necessity for the establishment of processes for the distillation of coal at low temperature is evident. The present waste of valuable materials by the continued use of beehive coke ovens will soon be indefensible.

Many plants in Germany are using brown coal on a large scale to produce low temperature tar, and this industry was an important source of lubricating oils, as well as fuel oils for internal combustion engines, during the war.* Creosote oils produced by this industry are exported to the United States under the name of "Avenarius Carbolineum," and they have been sold at higher prices than the domestic product made from ordinary coal-tar.

Other Uses for Oils.—Other tar oil products include:

Flotation oils, for use in the mining industry.
Lubricating oils.
Disinfectants.
Insecticides, including dip oil for sheep and cattle.
Light fuel oil, from the middle oil fraction, which is too volatile for wood preservation purposes. Possible uses are for Diesel engines, domestic furnaces and industrial heating.

Fuel oil, for industrial furnaces, from the fraction heavier than creosote.

Altogether, it should be possible to find high uses for the oils produced from the distillation at low temperature of more than 100,000,000 tons of coal annually. As the value of these oils may often be comparable with the value of the raw coal at the point of consumption, the economic importance of the recovery of oil products is evident. The recovery of a corresponding amount of oils by the present high-temperature processes would probably require the distillation of the entire present output of bituminous coal in the United States. With the general adoption of improved methods for utilization, however, the present enormous coal consumption should be greatly reduced.

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* Editorial by F. W. Parsons, *Gas Age-Record*, Dec. 31, **1921**, 873.

Motor Fuel.—In general, the tar oils will be more valuable for industrial applications than for fuel purposes and it will only be possible to sell surplus oil of the lighter cuts at a sufficiently low price to make them available as fuel for Diesel engines.

The light oils, however, belong to the gasoline class and can be marketed, after further preparation, as automobile fuels at a price which is comparable with the price of gasoline. The further preparation of the light oils is discussed by S. M. Darling* as follows: †

"Light hydrocarbon oils of the class including benzol make a serviceable motor fuel, and their effectiveness is somewhat increased when mixed with gasoline; the light oils can be used economically in this way and thus in a measure eke out the failing supply of gasoline. The indications are that the consumption of motor fuel within the next decade will be double the present gasoline production. In many quarters alcohol is looked upon as one of the ultimate sources, if not the main source, of motor fuel. Commercial alcohol and gasoline are not readily miscible; alcohol and benzol are; and, after the benzol is added to the alcohol, the mixture will take up a high percentage of gasoline. It may be well that a large use for the benzol production will serve as the connecting link between gasoline and alcohol, aiding in the introduction of alcohol as a staple market commodity."

Most of the benzol obtained from the distillation of coal, at either high or low temperatures, is recovered by scrubbing the oven gas, it consists largely of the more volatile hydrocarbons. Owing to the enormous consumption of gasoline, in recent years, it has become necessary to include a larger proportion of the lower boiling hydrocarbons, from the naphtha or kerosene fractions, in order to meet the increased demand. This low volatile gasoline has two rather marked disadvantages: (1) is more difficult to start the engine in cold weather, and (2) carbon deposits form more rapidly in the cylinders.

The blending of a certain proportion of benzol with the heavier gasoline counteracts these limitations. One of the principal constituents of coke-oven benzol is benzene (C_6H_6), which solidifies at 5.4°C.; consequently the commercial benzol

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* U. S. Bureau of Mines, "Better Utilization of Subbituminous and Lignite Coals," read before The International Railway Fuel Assoc., May, 1920.

† U. S. Bureau of Mines.

congeals to a viscous form in winter and can only be used when blended with gasoline. A mixture of the two motor fuels, in the proportion of 2 gal. of gasoline to 1 gal. of benzol, is now sold at some gasoline filling stations and is becoming very popular for winter use. The price of the mixture (in Schenectady) is 2 cts. more, per gallon, than for gasoline. The author's own car has an excellent engine; but when using ordinary gasoline in cold weather, it often starts with considerable difficulty and will not pull without stalling until warmed by running idle for 2 or 3 min. When using the benzol mixture at temperatures in the neighborhood of 0°C., the engine starts as readily as in summer and develops a good working torque almost as quickly as in warm weather. In colder weather the engine starts much more readily than with ordinary gasoline and does not require as much time for warming up before starting the car.

Synthetic Alcohol.—Ethylene is usually a constituent of gases produced by the distillation or gasification of coal. Hennell, in 1828, synthesized ethyl alcohol from ethylene. In a paper recently read before the Cleveland Institution of Engineers, Middlesborough, England, E. Bury, of the Skinningrove Iron & Steel Works, states that a large scale process has been worked out for the manufacture of synthetic ethyl alcohol from ethylene. Coke-oven gas is scrubbed with strong sulphuric acid, which absorbs the ethylene, and alcohol is afterward distilled from the acid.*

It remains to be seen whether a process of this type can produce ethyl alcohol cheaply enough for industrial uses. A similar process, however, is being used by the Standard Oil Company in this country for the preparation of isopropyl alcohol from hydrocarbons for special purposes.

ECONOMIC FACTORS

Fuel Storage.—One of the most important economic aspects of the substitution of carbonized fuels, for the bituminous coal now used for heating houses and buildings, is the elimination of trouble from spontaneous combustion in storage. This tendency puts a serious limitation on the activities of the bituminous coal mining industry in some parts of the country, by making it impracticable to mine coal in summer and to store it for winter

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* From BEAMA, London, Sept., **1920**, 178.

use. This is especially true in the case of some of the coals of the middle western states, which are especially liable to ignite spontaneously and which are largely used for winter heating The effect of this condition is to complicate the labor situation, owing to the fact that miners cannot work throughout the year. Sufficient wages must, therefore, be paid to hold the force together for the next season and this disturbs the uniformity of the wage scale in the coal mining industry as a whole. The lack of storage facilities at the mines is largely due to the liability of freshly mined coal to ignite spontaneously. This renders the continuity of the operation of the mines entirely dependent upon the regularity of the car supply.

The Clinchfield carbocoal plant (page 441) offers an example of the remedy for this situation. The establishment of carbonizing plants within a mining district renders it unnecessary to depart from the present practice of loading the output of the mines directly on the cars. Where only a short haul is required to deliver the coal to the preparation plant, the cars can be returned promptly to the mine and regularity of employment is assured for the miners. The preparation plant will operate continuously and maintain sufficient storage facilities to equalize the supply of raw coal from different mines, on the one hand, and the supply of carbonized fuel to the market on the other. Carbonized fuel can also be stored by the distributors and consumers. The greater regularity in the movement of cars over the short distances between the preparation plant and the mines should make it possible to contract for the coal requirements of the plant at a lower price than for coal intended for distant delivery.

A definite economic distinction must be drawn between carbonized fuels made for high uses, like domestic heating and metallurgical processes, and for low uses such as the generation of steam or gas. Fuels intended for high uses may be sold at much higher prices than those intended for low uses and may, therefore, be prepared by more expensive processes. Thus, a two-stage distillation can be used in the manufacture of carbocoal, and coal can be subjected to a long period of distillation at high temperature for the manufacture of metallurgical coke with a relatively small recovery of by-products. Semi-coke, on the other hand, should be made by a more rapid distillation at low temperature, which requires much less expenditure of fuel for heating the retorts. Water-gas at present is made from high-grade fuels—coke and gas oil. Cheaper gas can be obtained only from lower grades of fuel, such as bituminous coal and semi-coke.

In order to obtain cheaper fuel for generating electric power or for making gas, it will be advantageous to combine the preparation of fuel for high and low uses in a single plant, in order to be able to make a limited proportion of carbonized fuel for high uses as a profitable by-product during the summer season when the electric power load is light and when there is no gas heating load.

Another way to increase the returns from the by-products recovered from steam fuel is to operate a low-temperature retort in series with a by-product gas producer, as mentioned in this chapter. Owing to the investment required, this type of two-stage by-product recovery can be used to the best advantage in connection with the fuel required for carrying the base load in a power system. The available fuels should be graded on the basis of their nitrogen content, those richest in nitrogen being selected for this type of utilization.

Economic Location of By-product Power Plants.—With the exception of the old beehive coke ovens, the present types of processes for making gas and coke are carried out in plants located near the markets for the products. This renders possible the economic distribution of the primary products. The freight rates on coke are approximately 15 or 20 per cent. higher than for bituminous coal between given points, owing to its greater bulk; hence its transportation by rail is reduced to short distance hauls and the gas is distributed through short pipe-lines.

The same considerations apply in the case of low-temperature distillation where the semi-coke is a bulky product. Thus, a plant making semi-carbocoal should be located near the power plant in which the fuel is to be burned, while a dense fuel like carbocoal can be economically shipped from plants located near the mines.

The semi-coke produced by the Greene-Laucks process can be subjected to mechanical pressure during distillation. Hence this process is also adaptable to the production of lighter or denser fuels, according to the uses to which they are to be put. In some cases it may be desirable to locate the distillation plant near the point where the fuel is to be consumed. When carbonizing fuel for domestic use, however, its density will be such that the volume will be approximately the same as that of the raw coal from which it is made. Accordingly the plant may be located either near the mines or near the point of consumption. Fuel of this density should also be suitable for generating steam or making gas.

The general economics of power plant location have been discussed in Chap. V, in connection with fuel transportation, and it has been pointed out that it is usually impracticable to locate such plants near the mines. When we compare the relative advantages of a location near the market for the products, the following factors are of interest:

1. When the distillation plant is located near the mines, the fuel consumed in heating the retorts does not have to be transported to a distance. Any saving in freight charges, on the weight of this coal, will result in an increase in the net receipts for the products, similar to that obtained by a reduction in the price of coal at the mines. This saving, however, is obtainable only in the case of a dense product, owing to the fact that bulky fuels must pay a higher proportionate freight rate.

2. When the distillation plant is located near large centers of of population, the entire output of oven gas may be sold for high uses and the retorts may be heated with by-product producer gas made from semi-coke.

3. In the latter case, when the fuel consumption in the district is sufficiently great, the coal may be transported from the nearest large mining district through a pipe-line, as outlined in Chap. V. The reduction in the cost of transportation should far more than offset any advantages incident to the location of the plant near the mines. This arrangement will insure the continuous operation of the mines and coal may be stored under water near the plant.

4. When the semi-coke is to be gasified in a by-product producer, the distillation and gasification processes should be unified as far as may be practicable, as has been discussed in this chapter and in the preceding one. In a German process, the residual heat in the producer gas is utilized for the distillation of the coal.

5. When a coal preparation plant is located near the power plant, they may be placed under the same management.

Taking all factors into consideration, it would appear preferable to locate a coal-distillation plant near the power station in which the product will be utilized. Some further matters of interest are discussed in connection with coal-cleaning processes in Chap. VIII.

The distillation of coal at low temperature should open the way to the concentration of the preparation of most of the fuel used in cities in large plants where such operations may be conducted on an economical scale and on a multiple-product basis.

The principal products would be:

PRODUCTS	PRINCIPAL USES
Electricity	Power, light and heat.
Steam	Manufacturing and heating.
Hot water	Heating buildings.
Gas	Industrial and domestic uses.
Carbonized fuel	Industrial and domestic uses.
Semi-coke	Steam fuel.
Benzol, Diesel oil and compressed gas	Motor fuels.
Ammonium sulphate	Fertilizer.
Pitch	Roads, waterproofing, etc.
Tar oils	Various uses.

CHAPTER VIII

FINELY DIVIDED FUEL

By

F. Parkman Coffin[*]

INDUSTRIAL USES OF PULVERIZED COAL

Having reviewed the gasification and the distillation of solid mineral fuels by processes which are applicable for utilizing them as prepared steam fuels, as well as in the form of refined fuels for domestic and industrial uses, there remain to be considered the methods for mechanical preparation. The most widely used mechanical process consists in merely crushing run-of-mine bituminous coal to break up the larger lumps and reduce it to a more uniform product for convenience in conveying and firing. The process of crushing is carried out in the anthracite industry on a multiple-product basis for producing a number of commercial

Table LXXII.—Finely Divided Fuels

Designation	Use	Fineness of Product
Granulated	Firing over grate	⅜ in. to dust
Finely granulated	Further preparation	15 or 20 mesh and finer
Powdered	Rotary kilns and dryers (obsolete practice)	Large percentage through 60 or 80 mesh
Pulverized	Metallurgical furnaces,	98 to 99 per cent through mesh
	rotary kilns and	85 to 95 per cent through 100 mesh
	steam boilers	60 to 85 per cent through 200 mesh
Finely pulverized	Open-hearth steel furnaces and	95 to 99 per cent through 100 mesh
	steam locomotives; also pulverized anthracite for boiler firing	85 to 97 per cent through 200 mesh

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[*] Research Laboratory, General Electric Co., Schenectady, N. Y.

sizes, as mentioned in Chap. V. The crushing and sizing of bituminous coal is also carried on where lump coal is required for domestic use, and for the manufacture of producer gas and water gas or other industrial uses. The rejected screenings are usually sold at a lower price and are often available for further preparation, including pulverizing.

The present chapter deals primarily with the preparation and utilization of finely divided fuels. Several degrees of fineness may be distinguished as in Table LXXII.

The further preparation of finely granulated fuel includes the following processes:

Electrostatic cleaning (page 614),
Coke manufacture,
Low temperature distillation (Chap. VII), and
Pulverizing in tube mills (page 575).

HISTORY OF FIRING PRACTICE

The term "powdered coal" has been used since the early days of its application in cement kilns. The term "coal-dust firing" is occasionally used but is now practically obsolete.

The earlier successful applications were naturally made in connection with the types of furnace in which powdered coal could be burned most readily. These included rotary kilns and dryers, as well as annealing furnaces for malleable iron, which had very large combustion chambers. In these cases the coal was blown into the furnace, in suspension in the air for combustion, with a sufficient velocity to keep the coarser particles from settling out. The dimensions of these furnaces allowed the particles of coal to remain in the zone of flame for a sufficient length of time to be consumed before coming in contact with refractories.

When powdered coal was first applied to other types of furnaces, the cement kiln practice was naturally followed. In smaller furnaces the flame would frequently impinge on the wall opposite the burner. At furnace temperatures firebricks become somewhat plastic and are easily eroded by the particles of fuel or ash in the flame. Consequently a powdered coal flame, impinging on an opposite wall, or scouring against a sidewall, can soon erode the refractories and make a hole in the wall.

The best grades of commercial firebrick, such as are ordinarily used in heating furnaces, will begin to crush at a temperature of about 1,500°C. (2,732°F.); while safe operating temperatures for metallurgical furnaces range up to 1,350° or 1,400°C. (2,462° to 2,552°F.). The margin of safety, therefore, is relatively small and the reason is evident for the softness of the bricks at operating temperatures.

The use of pulverized coal in metallurgical furnaces is a development which has been worked out in the United States within the last 10 years. One of the pioneer plants where important development work was done was the American Iron & Steel Manufacturing Co.* at Lebanon, Pa. (now a part of the Bethlehem Steel Co.), where it was applied to many kinds of furnaces.

The present practice in the firing of pulverized coal in boilers, and in some types of metallurgical furnaces, differs from the methods originally used in cement kiln practice in two important particulars:

1. The coal is more finely pulverized.
2. The mixture of coal and air is blown into the furnace at a lower velocity—just enough to float it in.

These improvements have since been extended to the firing of rotary kilns as well, although most of them are still fired with relatively high velocities. This applies, however, only to the primary air, which is used for carrying the coal, and which represents only about 25 per cent. of the total air required for combustion (see page 64). In cases when low velocity has been used in rotary kilns it has been found that the resulting flame is longer and, therefore, the zone of higher temperature extends over a greater percentage of the length of the kiln.

In some of the modern types of burners, where the coal and air are mixed before leaving the burner pipe, the pressure at the tip of the burner pipe is about 0.5 in. of water, and the velocity of efflux ranges from about 40 to 50 ft. per second, which is about as low as can be used and yet carry the coal in suspension. This applies with coal of the usual degree of fineness, or 90 per cent. through 100-mesh and 80 to 85 per cent. through 200-mesh. Lower velocities would require still finer coal. In the long reverberatory furnaces used in copper smelting somewhat higher velocities are sometimes used and the pressure at the tip of the

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* Consult: C. J. Gadd, "Use of Powdered Coal in Metallurgical Processes," *J. Franklin Inst.*, September, 1916.

burner may be about 1.0 in. of water, the corresponding velocity being about 65 ft. per second. In each case the velocities mentioned are those due to the pressure-head alone, and the actual velocities may exceed these by the amount of the velocity-head. In furnaces for melting steel and malleable iron, the blast is directed downwardly upon the molten metal and much higher velocities are used (see page 526).

As soon as the blast enters the furnace, the gases are heated and they expand and lose velocity very rapidly, so that there is no impinging effect on the wall opposite the burner. The burner is located far enough away from side walls to avoid scouring action and yet not far enough to leave a cold zone at the side of the furnace. The maximum velocity permissible in the smallest section of the furnace, in the zone of highest temperature, is about 6 or 7 ft. per second.*

Fine grinding has been made commercially possible by the development of pulverizing machinery which was intended primarily for the grinding of cement materials. This machinery has been brought to its present stage of development since the use of powdered coal began in the cement industry. Several manufacturers have therefore endeavored to make a distinction between the product of modern pulverizing mills and the coarser fuel used for firing kilns in the older plants, by the use of the term "pulverized coal" in preference to "powdered coal." As is often the case, however, the older name persists, both terms being in quite general use among the users of this fuel. Some of the engineering companies in the business prefer one term and use it in their literature, and some the other.

Steam Boilers.—The earlier attempts to use powdered coal for firing boilers were naturally made by following cement kiln practice and in many cases these resulted in failure. A few installations were made, however, where powdered coal was burned with fair success under certain types of boilers, one of these being at the Erie Malleable Iron Works, where a battery of return tubular cylindrical boilers was fired with fuel which was somewhat more coarsely ground than is the present practice. This installation was run for some time and until the plant was finally shut down after arrangements were made for buying central station power. Powdered coal from the same milling

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* The above data are based on the practice of the Fuller Engineering Co. and others.

plant was also burned in malleable iron annealing furnaces, and its use for this purpose has been continued. A relatively coarse coal was also burned in the Bettington boiler, in several installations in South Africa, England and Canada.

Apart from a few instances, such as these, the history of the development of pulverized coal (using the more modern term) has been confined to its adaption to many industrial processes, until it began to be applied to standard types of water-tube boilers and to locomotives in 1915 and 1916. Its more recent application as a steam fuel is a natural sequence to its successful use in metallurgical furnaces, where it has only been used on a considerable scale since about 1914. The history of pulverized coal can, therefore, be concluded by a review of the various industrial applications.

INDUSTRIAL APPLICATIONS OF PULVERIZED COAL

The pulverizing of coal prepares it for use as a substitute for the naturally refined fuels, oil and natural gas. For many industrial applications it can be used more efficiently and effectively than lump coal. It can be fired automatically and the fuel and air are readily controllable. It can be handled and conveyed as a semi-fluid. These factors, together with others enumerated on page 534 (under heading 3), render it a refined fuel which is suitable for high uses like direct heating processes.

Pulverized coal is used on a multiple-product basis only to a limited extent, as when waste-heat boilers are used to generate steam as a by-product. These are frequently installed in connection with cement kilns and large metallurgical furnaces where the gases leave the furnace at a high temperature.

Opportunities for the further recovery of by-products rest in the recovery of hydrocarbons by subjecting the raw coal to a preliminary distillation at low temperature. The most advantageous applications for low volatile fuels are in connection with boilers and rotary kilns. The usual lower limit for volatile content, in coals used in metallurgical furnaces in pulverized form, is about 28 per cent. The lower limit for volatile content, however, varies with the design of the furnace and other applications may be found for semi-coke with a volatile content of from 15 to 20 per cent.

Rotary Kilns.[*]—The first successful commercial application of pulverized coal in the United States was made in 1895 by Hurry and Seaman, of the Atlas Portland Cement Co., for firing rotary kilns. It is now rapidly replacing more expensive fuels, such as oil, in parts of the country where coal is readily obtainable. The present extent of the use of pulverized coal in the cement industry is indicated in Table LXXIII, which contains a summary of the fuels used in 1917. All the coal was burned in pulverized form.

TABLE LXXIII[†]

Fuel	Number of plants	Number of kilns	Barrels of cement	Percentage of total
Coal	93	636	76,410,379	82.2
Coal and oil	1	24	6,492,713	7.0
Coal and gas	2	14		
Oil	18	103	8,680,313	9.4
Oil, coal and gas	1	5	1,230,797	1.4
Producer gas	1	1		
Natural gas	1	6		
	117	789	92,814,202	100.0

The plants using fuel oil are located in the states where oil is the principal regional fuel, such as Washington, Oregon, California, Arizona, and Texas. These five states contain 21 cement plants, while only 18 plants use oil, either wholly or in part. Some foreign plants also have American pulverized-fuel equipment.

The rotary kiln is lined with firebrick and high-refractory qualities are required since the temperature in the combustion zone ranges from 1,540 to 1,650°C. (2,800 to 3,000°F.). The lining must also be capable of withstanding decomposition by the chemical action taking place in the kiln. In some plants the air for combustion is forced through the clinker cooler, where it is preheated to about 400°C. (750°F.) before entering the kiln. This is a considerable aid to combustion.

The rotary kiln fired with pulverized coal has been applied

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[*] Consult also, "Pulverized Coal Burning in the Cement Industry," R. C. CARPENTER, *Trans. Am. Soc. Mech. Eng.*, **1914**, 85.

[†] "Cement in 1917," p. 360, *Mineral Resources of the U. S.*, U. S. Geological Survey.

in several other industries, as for calcining various minerals. (Calcining is a term used synonymously with burning, where the process involves the driving off of carbon dioxide or of water of crystallization.)

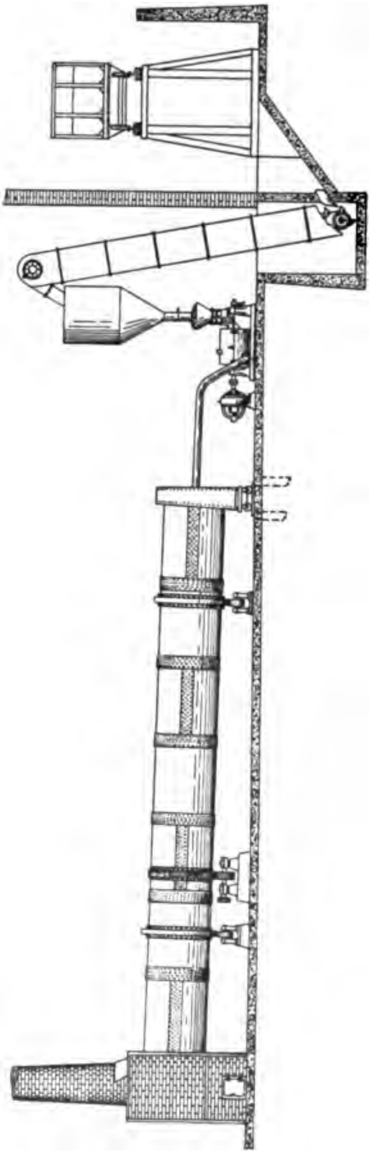

Fig. 105.—Cement kiln fired with pulverized coal on the "unit system," with "Aero" pulverizer.

Furnace refractories are made by calcining dolomite and magnesite. Lime is burned for making calcium carbide and for use in open-hearth furnaces. Gypsum is calcined for making plaster of paris and stucco by driving off the water of crystallization.

Potash is extracted from sericite,* greensand and marl, and is produced as a by-product of the Portland cement industry. It is distilled from the cement rock under treatment in the kilns and sublimes in the form of fine dust which goes up the flue. In some cement plants the flue dust is recovered by the Cottrell electrostatic precipitation process. This flue dust contains a large percentage of potash and is used for fertilizer purposes.

The older practice of burning limestone in vertical kilns is to charge the raw material in the form of fairly large lumps and to burn producer gas as fuel. The use of the rotary kiln, fired with pulverized coal, makes it possible to calcine the smaller sizes of

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* Sericite is a variety of mica made up of small elongated silver-colored shreds. It resembles talc.

limestone and to obtain a better quality of product. In some large installations the cost of operation has been reduced, less labor being required than with vertical kilns.

The charge should be crushed to a fairly uniform size. The actual fineness makes no difference as long as there is not too much difference between the largest and smallest stones; otherwise the coarse stones will rotate around the fines, allowing the latter to come out unburned.

The largest lime plant in the world was put in operation by the Air Nitrates Corporation at Muscles Shoals, Ala.* about the time when the war ended in 1918, but, like many other war plants, it was not placed in permanent operation. The practice of this plant is of interest. There were 7 kilns, 125 ft. long by 8 ft. in diameter, which were operated at a speed of one revolution in 1½ or 2 min. The slope was ½ in. to the foot and the rock was crushed so that all stones would pass through a 2½ in. ring and over a ½ in. ring. The unburned stone in the product was less than 1 per cent. The ratio of coal to lime burned was about 1 to 2.8 or 3 lb., according to the grade of the coal.

FIG. 106.—Rotary lime kilns fired with pulverized coal, Fuller-Lehigh system.

Ore Roasting and Nodulizing.—In the manufacture of sulphuric acid, pyrite is burned in special furnaces to sulphur dioxide and pyrite cinder. The latter is an oxide of iron con-

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* Consult article in *Rock Products*, July 10, 1919. The lime and pulverized coal plant was designed by the Fuller Engineering Co., Allentown, Pa., who also furnished much equipment.

taining about 2 per cent of sulphur, the original content being 48 per cent or more.

This 2 per cent sulphur content is too high for smelting the pyrite cinder as an ore of iron; also, it contains a large proportion of fine dust. It is, therefore, treated in nodulizing kilns of the rotary cement type which are fired with pulverized coal. The nodulizing operation consists of roasting off the residual sulphur and fusing the dust into nodules which can be smelted for making iron. Flue dust is also nodulized, thus making available products which have heretofore been rather expensive to recover.

Iron ore which contains a large proportion of water is mined at Mayari, Cuba, by the Spanish American Iron Co. This ore is clay-like and is mined with drag-line excavators. The total content of hygroscopic and combined water is about 35 per cent, and it is necessary to remove this weight before shipping the ore, and to improve its physical condition, in order to minimize dust losses in the blast furnace. It is therefore roasted in large nodulizing kilns* which are fired with pulverized coal.

Dryers.—Pulverized coal is used for drying cement rock before feeding it to the kilns and for firing rotary coal dryers in pulverizing plants. One plant has equipment for drying bauxite in a rotary kiln.

In the fertilizer industry it is used for drying tankage (garbage and sewage), for drying and slightly roasting phosphate rock, and for drying feldspar shale in rotary kilns for use as fertilizer filler.

Possibilities for Using Low Volatile Fuels in Rotary Kilns.—Pulverized anthracite has been used in cement kilns in an experimental way and it is believed by some authorities to have commercial possibilities in districts where limestone and clay or shale are used as raw materials. The Lehigh district, in eastern Pennsylvania and New Jersey, however, is the largest producer of cement of any district in the United States, and is the only important one favorably situated for utilizing anthracite culm. In this district cement rock is used as raw material and, being limited in its lime content, any contamination of the charge in the kiln by the use of a high ash coal would require the addition of a high-grade limestone to balance the mixture.† This is

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* C. M. Weld, *Bull. Am. Inst. Min. Eng.*, September, 1918.

† Credit for information: H. G. Barnhurst, Fuller Engineering Co., Allentown, Pa.

mentioned to indicate the possibility of using semi-coke, with a low ash content, as a fuel for rotary kilns.

In this application there is plenty of space for complete combustion in the long kiln lined with hot firebrick. The constituents of the coal ash are elements which also enter into the composition of the cement, so it is only necessary to analyze the ash and allow for the addition of its constituents when mixing the charge of raw materials.

Metallurgical Furnaces.—The most important application in which pulverized coal has made notable progress in the last few years is in the metallurgical field. Marked economies have been attained by the application of this fuel to furnaces used in the manufacture of iron, steel, copper, zinc, galvanized iron, and tin plate. The application of pulverized coal in the metallurgical industries is still in its infancy, but the list of plants using it shows that it has made good progress.*

The shortage of natural gas in some localities has been an incentive for the greater use of pulverized coal, and the high cost of fuel oil has provided an additional incentive. On the average, the substitution of pulverized coal as a fuel for metallurgical furnaces has resulted in a saving of about 33 per cent. of the fuel required when burning coal in other ways.

One feature of interest in this connection is a comparison of the percentage of excess air required when burning various fuels in metallurgical work.

TABLE LXXIV

Pulverized coal	5 to 25 per cent.
Hand-fired coal	100 to 125 per cent.
Stoker-fired coal	50 to 100 per cent.
Producer gas	50 to 75 per cent.
Natural gas	40 to 50 per cent.
Fuel oil	50 per cent. and upward.

The first cost of a plant for drying and pulverizing is less than for a producer gas plant. Pulverized coal firing has most of the advantages of gas or oil firing, when properly applied, and its field of application is constantly growing. When thoroughly mixed with a blast of air in correct proportion, it is practically a gaseous fuel. The principal difficulty is in connection with the ash produced in the flame. This is often a feature which limits

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* Consult *Gen. Elec. Rev.*, May, 1918, 378.

the practicability of pulverized coal firing for metallurgical furnaces.

The Iron and Steel Industry.—The principal applications of pulverized coal in the iron and steel industry are for the following classes of furnaces:

- *Heating Furnaces:*
  - Heating, re-heating and forging.
  - Continuous heating, for blooms and billets.
  - Annealing malleable iron and steel castings and plates.
  - Sheet and pair (steel bars are heated for rolling into plates).
  - Busheling and pudding (malleable iron).
  - Tin pots.
  - Galvanizing pots.
- *Melting Furnaces:*
  - Open-hearth steel.
  - Malleable iron.

Forging Furnaces.—A typical furnace for heavy forgings is shown in Fig. 107, equipped with a Fuller-Lehigh pulverized coal burner in one end. For rough work, the fuel is often burned in the same compartment with the work. For more finished work, where ash and slag may have a deleterious effect, a separate combustion chamber is frequently provided, and the two compartments are separated by a low bridge-wall, as shown in dotted lines in Fig. 107. A large part of the ash collects in the bottom of the combustion chamber, while the flame plays over the bridge-wall and is long enough to extend over the work and to heat it by direct radiation. When substituted for natural gas, increased thermal efficiencies have been attained, owing to the greater

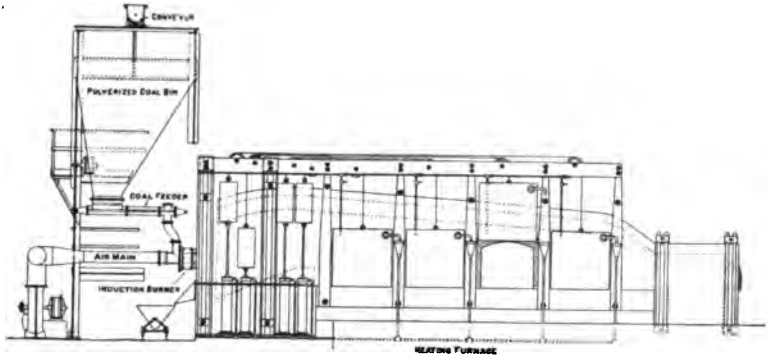

Fig. 107.—Heating furnace for forgings, Fuller-Lehigh system.

proportion of radiant heat emitted by the flame. In small forging furnaces the coal and air are sometimes introduced through opposed tuyeres, in order to avoid the impingement of the flame on the wall opposite the burner. This practice is illustrated in Fig. 107. Opposed flames have also been used in burning natural gas.

A typical small forging furnace is shown in Fig. 108. This is equipped with opposed tuyeres and the secondary or volume air is divided between the two, while the coal is fed into one side only, being carried by the primary air which forms a small proportion of the air required for combustion. 'When warming a cold furnace, a hot spot is visible where the blasts impinge. As the brickwork becomes heated, this spot fades to a uniform glow which fills the whole interior. It is claimed that the introduction of all the coal on one side gives the best results. This furnace is located in the drop forge shop of the American Locomotive Company, in Schenectady, and the burners form part of a patented system. The fuel feeder is described on page 679.

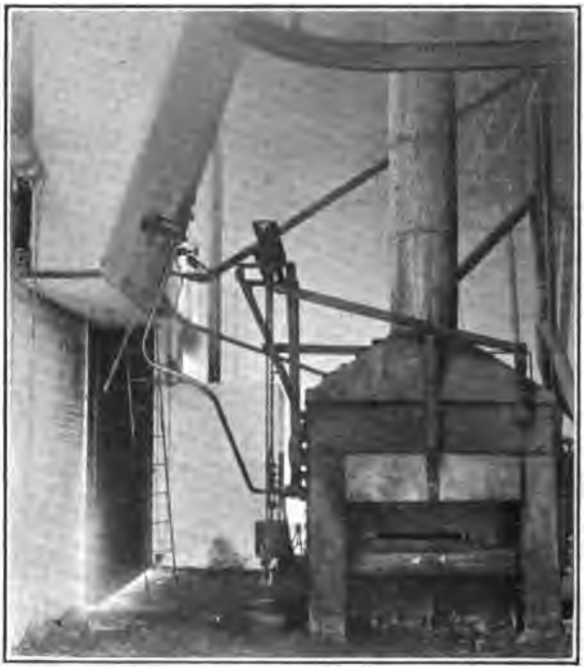

FIG. 108.—Small forging furnace with pneumatic siphon coal feeder, American Locomotive Company.

Continuous Heating Furnaces.—These are very long furnaces which are equipped with burners in one end. The work, which consists of blooms or billets for forging or rolling, is introduced in the opposite end of the furnace and is gradually worked towards the hot end, finally being removed through side doors. These furnaces offer ideal conditions for the burning of pulverized coal. When looking through a side door, no flame is visible, the whole interior being filled with a uniform glow.

In a furnace recently designed by the Fuller Engineering Co., two or more combustion chambers are located directly under the track or platform which carries the work, and the ash and slag are mostly deposited before the products of combustion rise through ports into the work chamber.

Sheet Mill Furnaces.—One of the most modern installations for burning pulverized coal in a sheet-rolling mill is to be found in the plant of the Newport Rolling Mill Co., at Newport, Ky.* Natural gas was formerly used as fuel, and when the supply failed it was temporarily replaced by hand-fired and stoker-fired coal. The entire plant has now been equipped to operate with pulverized coal, which will also be used for some new furnaces under construction.

The furnaces now operating include 20 sheet mills, served by 23 furnaces. The original plans called for eight annealing furnaces, to replace an equal number of hand- and stoker-fired furnaces. Two were re-equipped at first and the output, when burning pulverized coal, so greatly exceeded expectations that it was only necessary to re-equip six furnaces to handle the same output as eight stoker-fired furnaces of the same size. The galvanizing department has eight pots. One Costello continuous sheet annealing furnace is also fired with pulverized coal.

The following figures have been submitted as average production data obtained at the plant. On the slab heating furnaces, maximum fuel consumption of 180 lb. of coal per ton of product, though it is stated that considerably less than this amount per ton may be taken as the average run. On the sheet and pair furnaces, fuel consumption covering long periods has not exceeded 275 lb. of powdered coal per ton of sheets produced. On the annealing furnaces, fuel consumption using powdered coal is re-

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* Consult: "Burning Pulverized Coal in a Sheet Mill," *Iron Age*, Dec. 11, **1919**; "Burning Powdered Coal in a Rolling Mill," by H. T. Matthew, *Combustion*, April, **1920**.

ported well under 170 lb. of coal per ton of sheets annealed On the galvanizing pots, fuel consumption below 110 lb. per ton, on the average, and considerably less than this average for favorable weight sheets.

The equipment was supplied by the Quigley Furnace Specialties Co., the fuel being conveyed from the milling plant to the furnace bins by the air transport system (see page 638). All bins are of steel plate, entirely enclosed and dust tight. There is one bin for each group of sheet and pair furnaces, one for each annealing furnace, and one for each pair of galvanizing pots. In order that the furnace operator may determine the amount of fuel available for firing, each furnace bin is provided with a fuel gage, having an indicator conveniently located.

The Falcon Steel Co.* has recently built a new sheet mill at Niles, Ohio, in which pulverized coal is used as fuel for all purposes. This is a modern plant equipped with electric drive throughout, most of the power being purchased. Two Badenhausen boilers, each of 200 hp. rating, furnish steam principally for heating rolls and for operating air compressors and shears. These are fired with pulverized coal from a 10-ton bin by means of four feed screws which are geared to a line shaft and are operated at constant speed by a 5-hp. motor (see page 665). Each boiler is equipped with two burners.

The furnaces include:

Seven Hagan-Allis double-chamber sheet furnaces.
Four double-chamber pair furnaces.
One Costello continuous-annealing furnace.
Two double-box, double-chamber annealing furnaces.
One blue-annealing furnace.
Three galvanizing pots.
One grease kettle.

The Quigley air transport system (page 638) is used for distributing the fuel from the milling plant to the furnace bins, and the entire pulverized coal equipment was designed or furnished by the Quigley Furnace Specialties Co. Over a period of 3 months' operation the total coal consumption at the plant averaged 335 lb. per ton of sheets in the warehouse.

The Newton Steel Co., at Newton Falls, Ohio, has another modern sheet-rolling mill, which commenced operations in the spring of 1920. All the heating furnaces, as well as the boilers,

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* Extract from article in *The Blast Furnace and Steel Plant*, May, 1920.

are fired with pulverized coal, the entire equipment being furnished by the Fuller Engineering Co. The pulverized coal is conveyed over a distance of about 1,000 ft. by means of the Fuller-Kinyon conveying system (page 641), which distributes it from the milling plant to the furnaces.

Open-hearth Steel Furnaces.—Furnaces for melting and refining steel by the basic open-hearth process are fired with pulverized coal in a number of plants. A furnace of this type is shown in Fig. 109, equipped for firing with pulverized coal by the Bonnot system. The practice is to fire the fuel from both ends of the furnace on the reversing principle with a high velocity blast. In some installations the air required for combustion is delivered to the burner at a pressure of 1 lb. per square inch by a centrifugal compressor, while in others it is delivered by a fan blower at 8-oz. pressure.

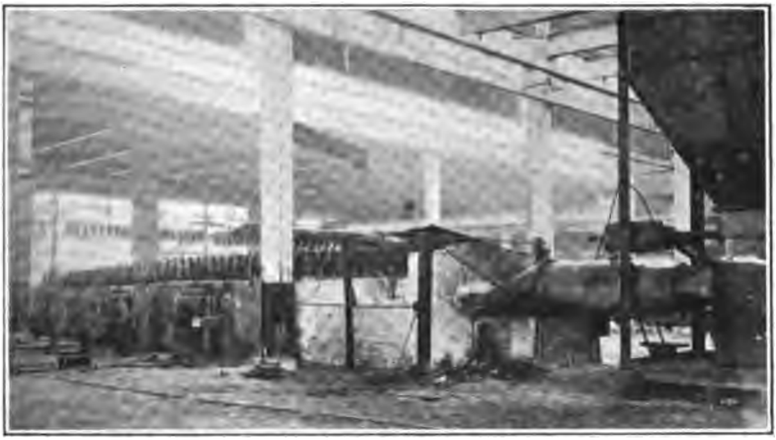

FIG. 109.—View of 15-ton melting furnace for malleable iron, General Electric Company, Erie, Pa.

N. C. Harrison* of the Atlantic Steel Co., Atlanta, Ga., has reviewed the experience of his company as follows: The hearth of a pulverized coal open-hearth furnace is practically the same as the hearth of any other open-hearth furnace. The uptakes, slag pockets and checker chambers are entirely different. The uptakes are made as small as possible, so as to hold the gases in the furnace as long as possible without blowing; and the slag pockets

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* Condensed from "Pulverized Coal as a Fuel," *Mech. Eng.*, August, 1919.

are made as large as possible, so that the gases will have a slow velocity going through them, thereby depositing a large percentage of the heavy particles that are in the outgoing gases. On account of this heavy deposit, removable slag pockets, or very deep stationary pockets, should be used to collect this accumulation over the tun of the furnace. Where removable slag pockets are used, they are taken out and cleaned and replaced about every 2 weeks. Only one checker chamber is needed on each end of the furnace. If the checker chamber is large enough, these chambers should be built up with large tiles and laid in such a manner as to form vertical flues, having openings of at least 6 by 9 in., or better 9 by 11 in. In some cases, no checkers are used at all, but the chambers are filled with baffle walls with openings from the outside, so that the accumulation between these baffle walls can be raked out (see page 531). All passages from slag pockets to stack must be as straight as possible and, wherever bends must be made, some agitating device should be installed. The reversing valves are usually of the mushroom and damper slide type.

The best coal for use in pulverized form in open-hearth practice is a bituminous coal as high in volatile matter as possible and preferably low in ash. It should never contain below 32 per cent of volatile nor more than 8 per cent of ash. It is nesessary that the coal be as finely ground as possible, so that about 97 per cent will pass through a 100-mesh sieve; preferably 90 to 93 per cent, and not less than 85 per cent, through a 200-mesh sieve; and from 70 to 75 per cent through a 300-mesh sieve. This is necessary for quick combustion and for the elimination of sulphur. By this very fine pulverization the attempt is made to have complete combustion before the flame strikes the bath, thereby burning out the sulphur in the coal to SO_2 gas, which passes up the stack. In order to get this complete combustion before striking the bath, some 6 or 8 ft. are necessary from the end of the burners to the bath.

The advantages and disadvantages from the use of pulverized coal, as compared with hot producer gas as a fuel for open-hearth furnaces, from observation of its use up to date are as follows:

The gas is of a more even chemical composition, and all the heat is generated in the furnace; while in the case of the gas producer from 18 to 25 per cent of the heat units are lost in the producer itself when converting the coal into gas. The higher flame temperature results in a greater number of heats per week. Open-hearth furnaces using powdered fuel, operated on a very low-fuel consumption, fully equal to the best producer gas practice, and much better than the average of the older plants in this country; at the Atlantic plant the coal consumption is about one-third less than with producer gas. Coal can be pulverized in plants of about 100 tons daily capacity and delivered to the furnace for approximately 50 cts. per ton, which is about the same as the costs for gasifying coal in gas producers.

The use of this fuel in metallurgical furnaces has been developed to only about 75 per cent of its ultimate value. In the Atlantic plant this open-hearth furnace has been shut down oftener than the producer gas furnace of the same size, due to checkers and slag pockets filling up with cinders and slag, after about 80 heats. It is believed, however, that the company is gradually overcoming these troubles by decreasing the size of the

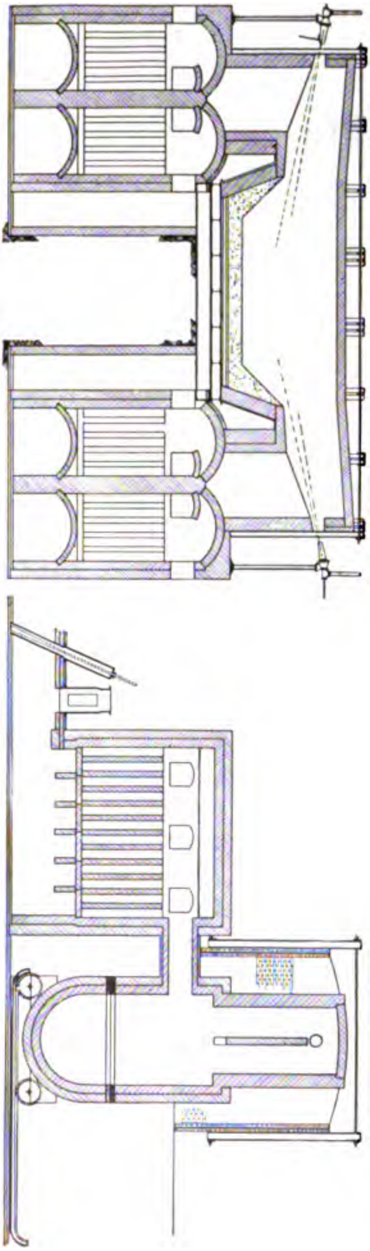

FIG. 110.—Holbeck pulverized coal system applied to a typical open hearth furnace (published through the courtesy of The Bonnot Company, Canton, Ohio).

uptakes and enlarging the slag pockets, as mentioned above. Now, only the fine particles are going to the checkers and are being blown off daily by compressed air. By these alterations, it is expected to get much longer life out of the checkers, and consequently longer runs out of the furnace. As a result of this continued development, it is expected that inside of 6 months there will be obtained a 25 per cent. increase in production over the gas producer furnaces of the same size.

Sulphur does not give any trouble as long as there is a good draft and the furnace is working hot. The Atlantic plant is now using coal with over 1 per cent. of sulphur and getting good results. If checkers get clogged up and the furnace begins to blow, due to lack of draft, there is trouble with the bath taking up sulphur. The furnace is under complete control of the first helper, as to amount of coal being used, as well as the air blast and temperature. The flame, using the same coal as on gas producer, is hotter, which allows use of a greater percentage of scrap per ton of steel, thus reducing the consumption of high-priced pig iron; also it enables a greater number of heats per week.

The finished steel is quieter in the moulds, due to not being over-oxidized, as the coal coming directly in contact with the bath has a greater reducing action. It is reasonably certain that the oxidation losses are less with pulverized coal than with producer gas. All gas-house troubles are eliminated (cleaning fires, burning-out flues, etc.), although the pulverizing plant must be given attention as to dryness and fineness. Refractory costs have been greater on the furnace using pulverized coal than on gas producer furnaces. Harrison believes, however, that the steadily increasing familiarity with the use of this fuel will enable his company to reduce this item nearly to the corresponding cost in producer gas furnaces.

The equipment for preparing and firing pulverized coal at this plant was furnished by the Fuller Engineering Company.

Other Installations.—The pioneer installation for firing basic open-hearth steel furnaces was made by the National Malleable Castings Co., at Sharon, Pa., about 1914, and has been operated successfully since that time. Pulverized coal has displaced fuel oil without any sacrifice of tonnage or quality of the product and with very gratifying economies.*

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* Consult also: "Pulverized Coal Systems in America," by L. C. HARVEY, Fuel Research Board *Special Report*, **1**, London, 1919. Also "Pulverized Fuel, Its Use and Possibilities," by W. J. DICK, Commission of Conservation of Canada, Ottawa, **1919**.

In some recent open-hearth furnace installations, built from designs made by the Quigley Furnace Specialties Co., vertical baffle walls have been used in the regenerative chambers in place of checkers. These are staggered to allow the gases to flow alternately up and down through the spaces. All deposits of ash or dust collect at the bottom of the chambers, where doors are provided in the side walls for their removal by means of rakes. This has obviated the difficulties encountered where the ash deposits have filled the checkers.

A number of basic open-hearth installations have been made at plants of the United States Steel Corporation. Pulverized coal has been applied to the acid open-hearth process but has not been found suitable. The possibility of cleaning pulverized coal by the Trent process (page 628) may enlarge its field in melting operations.

Malleable Iron-melting Furnaces.—Pulverized coal has been used in a number of malleable-iron foundries for annealing castings, some of the installations dating from the earlier period when more coarsely powdered coal was used. Until recently, however, it had not been successfully used for melting purposes.

Installation at the Erie Works of the General Electric Co.*—What is probably the pioneer installation for melting malleable iron was made in 1919 at the malleable foundry of the General Electric Co., at Erie, Pa. This is an air melting furnace with a capacity of 10 or 15 tons and is equipped with a 22-in. Arrowood burner (page 641). Considerable experimenting was necessary at first to obtain the most satisfactory arrangement and the furnace has recently been greatly simplified by discarding three features which were considered necessary at the start.

The first was a water cooled damper, at the back bridge wall, which was thought necessary for controlling the stack draught. The second was a combustion chamber between the burner and the furnace. This was thought essential to obtain complete combustion of the coal. The third was a top blast, which was installed because it was used in all malleable iron foundries. The company's engineer, however, considered this custom to be the result of superstition rather than necessity and the top blast was finally discarded. These sweeping changes have added greatly to the efficiency and simplicity of operation of the furnace.

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* The author is indebted to H. E. Bailey, of the Erie Works of the G. E. Co. for information.

Two heats are run off per day. The first is started with a cold furnace and tapped off in about 4.5 hr. after lighting the burner. The second heat is started with a hot furnace and is poured in about 3.5 hr. after starting the burner the second time.

The advantages derived in melting malleable iron with pulverized coal, as compared with hand-firing, are as follows:

1. Increased economy. The ratio of coal to iron in hand-firing, under the best conditions, was not over 1 to 2.5; while with pulverized coal a ratio of 1 to 4.5 is obtained.
2. Owing to complete control of the melting conditions and of the speed of the operation, the heats may be tapped at exactly the time set in advance. This does not vary more than five minutes from day to day.
3. A hotter and more fluid iron is obtained, which is very desirable in malleable iron practice. This cuts down the losses from miss-run castings.
4. The cost of repairs to the furnaces has been reduced approximately 50 per cent.
5. The labor saving, in running the furnace, is about one and one-half men.

Other Installations.—Similar installations are being made by the Ground Coal Engineering Co. (which furnished the burner for the above furnace) in foundries at several other plants.

In 1919, a malleable-melting air furnace was put in successful operation by the Combustion Economy Corporation, with pulverized coal as fuel, in one of the largest malleable iron foundries in the United States. This furnace was of 10 tons capacity and was formerly fired by hand. Only a few slight changes were necessary in the firebox, such as filling the ashpit, lowering the front bridge wall, removing the top blast and altering the front of the firebox to provide for the burner pipe.

The general dimensions of the furnace are as follows: Length between bridge walls, 15 ft. 6 in.; width at tapholes, 5 ft. 6 in.; firebox, 40 by 59 in.; diameter of stack, 29 in.; height of walls at tap holes, 31 in.; depth of metal at tap holes, 9 in. This is considered a very small furnace. On larger furnaces the results should be even more favorable.

The method of introducing the burner into the furnace is illustrated in Fig. 111. The mechanism will be discussed in a later section.

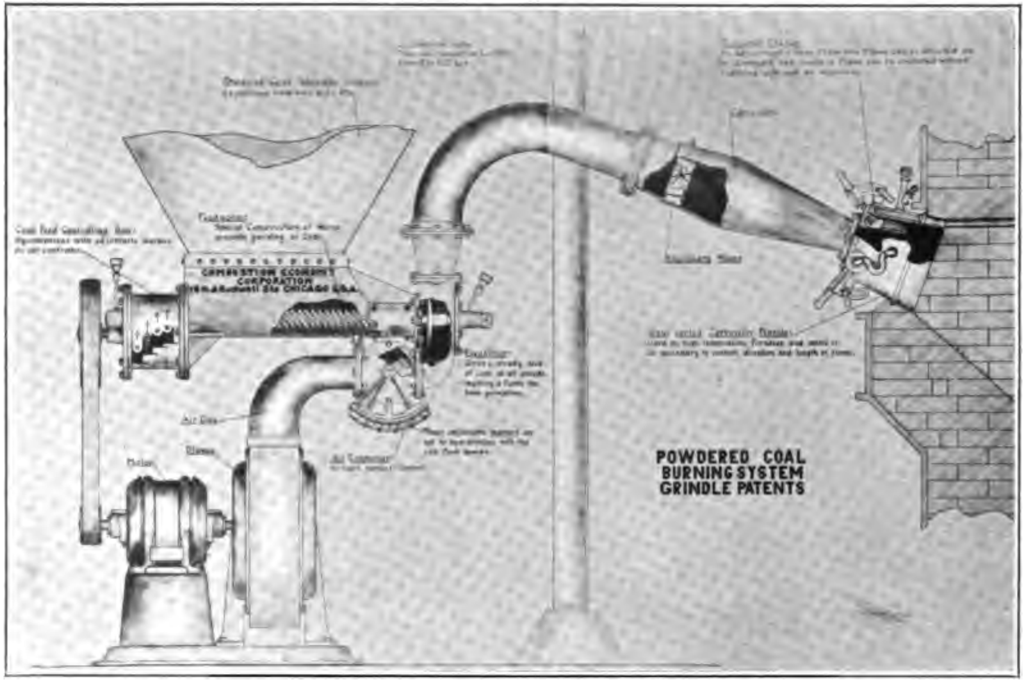

FIG. 111.—Burner and feeding mechanism for malleable iron melting furnace.

TABLE LXXV.—COAL

Analysis of coal used				Sieve test
Moisture	1.64	Volatile matter	37.43	200-mesh...76 per cent.
Fixed carbon	54.98	Ash	5.95	240-mesh...72 per cent.
Sulphur	0.768	B.t.u.	13,605	300-mesh...56 per cent.

TABLE LXXVI.—COSTS BASED ON THE FOLLOWING PRICES

Metals per Net Ton

Pig iron	$27.20
Steel scrap	20.50
Malleable scrap	24.50
Remelt scrap	25.00

Fuel

Fuel oil	$0.058	gal. delivered
Lump coal	5.50	ton delivered
Powdered coal*	7.04	ton pulverized

Labor

$0.55 per hour

* NOTE.—Pulverizing costs based on a capacity of 5 tons of pulverized coal per hour, plus 100 per cent. overhead.

TABLE LXXVII

Method of firing	Hand-fired	Fuel oil	Powdered coal
Capacity of furnace, tons	10	10	10
Average melt, tons	9½	9	9½
	Per cent. of metals in charge		
Pig iron	47	58	42
Steel scrap	6	0	7
Malleable scrap	13	8	17
*Remelt scrap	34	34	34

* NOTE.—The above mixture is based on a remelt of 34 per cent. for all furnaces, and a charge which, after pouring into castings, will analyze as follows: carbon, 2.50 per cent.; silicon, 0.85 per cent.; manganese, 0.30 per cent.; sulphur, 0.065 per cent.; phosphorus, 0.15 per cent.

TABLE LXXVIII

Fuel	Hand-fired coal	Oil	Powdered coal
Capacity, tons	10	10	10
Average melt, tons	9½	9½	9½
	Cost per ton melt		
Metal charge	$25.69	$26.23	$25.40
Fuel delivered at plant	2.56	4.96	2.26
Firing labor	0.75	0.33	0.30
Fuel handling labor	0.14	0.01	0.03
Brick	0.79	0.57	0.56
Skimming bars	0.18	0.14	0.15
Power	0.04	0.07	0.07
Total cost	$30.15	$31.41	$28.77

TABLE LXXIX

	HAND-FIRED COAL	POWDERED COAL
Air pressure at furnace, ounces	2–3	05–1
Diameter main blast pipe, inches	18	15
Volume of main blast, cubic feet per minute	3,500	3,500
Time of melt, hours		
Hot furnace	5.5	3.5–4
Cold furnace	6.5–7	4.5–5
Coal per ton of iron melted, pounds	940	600

PERCENTAGE OF SAVING

Coal	31
Pig iron replaced by scrap	18
Time of melt	30
Labor	60
Skimming bars	30
Cost of repairs	29

In comparing the pulverized coal-fired furnace with the hand-fired furnace, there are a number of other advantages which cannot be expressed in figures. These have been summed up as follows:

Less slag to dispose of, including all melted ash.
Practically no ashes to dispose of.
No cleaning of clinkers from fire box.
No grate bars. No top blast.
No smoke at any time.

More uniform analysis of castings.
Cleaner furnace surroundings.
Easier on workmen, making them more satisfied, as there is less poking, leveling and skimming.
Decreased oxidation of metal.

The pulverized coal equipment for this installation was designed and furnished by the Combustion Economy Corporation

It is suggested that, in malleable iron foundries where it has not paid to pulverize the fuel required for annealing alone, it should now be possible to use pulverized coal for melting, annealing, core baking and for generating steam, thereby making it possible to pulverize the fuel on a sufficient scale to prepare it economically.

Copper and Other Metals

In the copper-mining industry the ore must usually be smelted near the mines in order to avoid high transportation charges. The choice of cheap fuel is limited to supplies which can be obtained within a reasonable distance and this is frequently a low-grade coal of a non-coking variety. Coke for blast furnaces must usually be obtained from distant sources at a much higher cost than local coals. The economic conditions in the copper industry are, therefore, particularly favorable for the use of pulverized coal; moreover, the long reverberatory furnace offers very favorable conditions for the application of this fuel.

It is burned in the following types of furnaces in the copper, lead, zinc and tin industries:

Reverberatories, for roasting, smelting and melting; blast furnaces, as a substitute for a part of the coke; and cylindrical mechanical roasters.

COPPER SMELTING

Blast Furnaces.—The larger sizes of copper ore are most economically smelted in blast furnaces and the fuel practice differs with the composition of the ore, as to sulphur content, as follows:

1. *Coke smelting* is used for non-pyritic ores.
2. *Partial pyritic smelting*, in which a part of the heat is generated by the combustion of the sulphur content and the remainder by coke added to the charge. This is the most important variety of blast furnace practice in the United States, and the most

recent development is the substitution of pulverized coal for 30 to 50 per cent of the coke.

3. *Pure pyritic smelting*, in which most of the heat is generated by the combustion of the sulphur content, and only a little coke is added, which is consumed before it reaches the oxidizing zone.

Reverberatory Furnaces.—Much of the concentrated ore is in sizes which are too small for smelting in the blast furnace. Also, there are certain by-product materials to be resmelted, such as slags and flue dust. The reverberatory furnace is better suited to the smelting of fine materials.

4. *Pyritic ores*, with a sulphur content which is too high to allow of direct smelting in reverberatory furnaces, are first roasted. This is usually done in cylindrical mechanical furnaces, where the excess sulphur is burned out without the use of carbonaceous fuel, except for the occasional ignition of cold furnaces. Fuel oil or pulverized coal is used for ignition. The roasted ore is afterwards smelted in reverberatories.

5. *Refractory ores*, in which the rocky portion contains a large amount of silica, and which are mined in localities where fluxing materials (such as limestone or fluxing ores) are not obtainable, are treated by wet processes which remove the metallic portion by solution. It is usually necessary to alter the form of the ore by roasting it, in order to render the metallic compounds soluble in the liquids used. This is done in roasters of the McDougall, Wedge or Herreshoff type, in which the charge is mechanically stirred: These are fired with fuel oil or pulverized coal, burned in independent fire-boxes at the various hearths. Hand-fired coal was formerly used, but proved to be very unsatisfactory, owing to lack of control over the atmosphere in the furnace, which must be oxidizing. The final wet processes used for the extraction of the copper and other metals include chemical and electrolytic methods.

The smelting of copper is often preferred to wet processes for large scale operations, especially when the ore can be rendered fusible by the additon of ores from other mines having a gangue which will flux with the gangue of the ore to be smelted. Pulverized coal is coming into very general use in reverberatory furnaces at large smelting plants, the fuel used having a volatile content of at least 33 per cent.*

The operation of smelting copper consists in melting the ore and

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* W. J. Dick, *loc. cit.*, p. 532.

fluxing material, in order to allow the metallic sulphides to separate from the oxidized portion by gravity. These two portions are called, respectively, the matte and the slag. The matte consists mainly of a mixture of copper and iron sulphides and precious metals, and is subsequently subjected to further refining. The slag is formed in much greater quantity and is "skimmed" liquid.

The operation of smelting copper, therefore, differs from the smelting of iron, in that the metal is reduced to the metallic state and the reduction of metallic oxides by carbonaceous fuel takes place as a secondary reaction rather than a primary one. The primary function of fuel is to generate heat or melt the ore.

Reverberatory Smelting.—Some pioneer experiments were made at different smelting plants between 1905 and 1907. In one plant the experiments were discontinued when fuel oil became locally available, and in others owing to the limitations of the crude apparatus used. These experiments did, however, indicate the economic possibilities of this fuel for smelting copper.

International Nickel Co., Copper Cliff, Ont.*—In 1909, some experiments were made by D. H. Brown and G. E. Silvester, of the Canadian Copper Co., which operates plants of the International Nickel Co. in Canada. As a result, it was decided to instal equipment for smelting copper-nickel ore and flue dust at the smelter at Copper Cliff, Ont. The furnaces were designed to be fired with pulverized coal and they were put in commission in December, 1911, and almost from the first the new method of firing proved a success and it has been used at this plant ever since.

There were originally two reverberatory furnaces, but only one is operated now. This is 112 ft. long and 19 ft. wide. The bulk of the charge is calcined ore from the Wedge furnaces, which amounts to 80 or 90 per cent. of the total charge. The coal used is bituminous slack, having about the following analysis:

Vol., 35 per cent.
F. C., 52 per cent.
Ash, 13 per cent.
Sulphur, 1.5 per cent.

The ash content has frequently run as high as 17 per cent. The moisture varies from about 5 to 9 per cent., according to the season.

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* Condensed from "Pulverized Fuel," by W. J. Dick, pp. 11 and 25, Commission of Conservation of Canada, **1919**.

It has not been found practicable to reduce this much below 1.5 per cent.

The coal is fed from the storage bin by five feed screws, which drop it in front of an air blast by which it is blown through five 5-in. pipes, projecting through the bridge-wall of the furnace.

The blast is supplied at 5 or 6 oz. pressure by two No. 8 Sturtevant blowers. This primary air is supplemented by secondary air drawn in by natural draft through openings in the bridge-wall.

The draft is controlled by a damper in the flue and is usually equivalent to from ¾ in. to 1 in. of water. The fuel supply is controlled by the speed of the feed screws. At full capacity, about 100 tons of coal can be burned in 24 hr.

For the month of April, 1919, 2,094 tons of coal were burned and 13,547 tons of solid charge was smelted; or about 6.5 tons of charge per ton of coal. In the old grate-fired type of furnace the best ratios obtained were from 4 to 4.5, and this economy was attained only in the best managed plants and after a long period of evolution. For a day or two at a time the Copper Cliff plant frequently smelts over 7 tons of charge per ton of coal.

The working temperature of the furnace ranges from about 1,525° to 1,575°C. (2,800 to 2,900°F.) at the hottest part, gradually diminishing to about 1,100°C. (2,000°F.) at the flue end. A higher temperature could readily be obtained but would cause undue wear on the furnace roof. The temperature is at all times under control through the rates at which the fuel is fed and the ore charged.

With grate firing it was customary to drop a large amount of ore at intervals through holes in the roof near the firing end. Pulverized fuel firing makes it possible to feed the ore continuously along the sides of the furnace. A longitudinal hopper is mounted along either side above the roof, and the ore runs down through 6-in. pipes, spaced about 2 ft. apart, which enter the furnace through holes in the roof close to the side walls. The hopper is kept full of ore and this banks up in continuous piles along the sides of the furnace. As the charge smelts and runs away, ore feeds down continuously from the hopper, and very little of the brick work of the furnace is exposed to the flame other than the roof; consequently this is the only part requiring regular repairs. Portions of the roof are replaced every 6 or 8 months and a complete new roof is put on about every two years.

Anaconda Copper Mining Co.—One of the next installations was made in 1914 at the Washoe Reduction Works at Anaconda, Mont. This is the largest copper-smelting plant in the country and the reverberatory furnaces are all fired with pulverized coal. Coal with an ash content as high as 22 per cent has been used and it was found easier to keep the flues clean when using this coal than when using another grade containing only 9 per cent of ash.*

The coal-milling plant is equipped with Raymond mills which have a total capacity of nearly 1,000 tons per day. When operating nine reverberatory furnaces and two copper-melting furnaces, this plant burns about 800 tons of coal in 24 hr. and smelts approximately 5,000 tons of material.

The reverberatory smelting furnaces formerly used direct grate-firing and smelted about 4.25 tons of charge per ton of coal. Using pulverized coal they now smelt about 6.75 tons of charge per ton of coal. Not only has the fuel ratio been increased by more than 50 per cent but the capacity of the furnaces has been almost doubled.

The same company formerly used small furnaces of the open-hearth type for melting copper calcine at Great Falls, Montana. These were equipped with double checkers at each end and the necessary reversing valves. They were fired by gas made in automatic producers from a very low-grade bituminous coal mined in the vicinity. These furnaces operated continuously for many years. In 1913 and 1914, the installation was rebuilt with reverberatory furnaces which were originally intended to be fired with gas generated in huge producers, which, however, proved to be unsatisfactory. In the meantime, pulverized coal had been successfully applied to the furnace at Anaconda, and it was soon substituted for the producers at Great Falls as well. The coal used at this plant has an ash content of about 23 per cent. When using either grate-firing or producer gas, from 2 to 2.5 tons of charge were smelted per ton of coal, while between 4.5 and 5 tons of charge are smelted per ton of pulverized coal. The radiant heat from a producer gas flame is much less than from a pulverized coal flzme, and the gas must be preheated to obtain a good rate of smelting.

The temperature in the combustion zone of a reverberatory furnace with grate-firing is about 1,300°C. (2,400°F.), while

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* W. J. Dick, *loc. cit.*, p. 27.

with pulverized coal it averages about 1,410°C. (2,600°F.). The gases leave the furnace with a temperature of about 1,100°C. (2,000°F.) and the residual heat is utilized for generating steam in a waste heat boiler.

It is evident that the proportion of available energy above the temperature of the flue gases is about 50 per cent greater in the case of pulverized coal. Smelting only commences at about 1,190°C. (2,200°F.) and in one case we have a differential of only 110°C., whereas in the other case we have a differential of about 220°C. The rate of heat transfer by radiation varies as the difference in the fourth powers of the absolute temperatures of the hotter and cooler bodies. In this case a differential of 220°C. will enable the flame to radiate 2.3 times as much heat as when the differential is only 110°C., and the reason for the increased output of the furnace is evident.

In the last few years pulverized coal has almost entirely supplanted grate-firing in reverberatory furnaces in the copper industry and, in a number of instances, has replaced oil firing. The furnaces in use at most of the large smelters are of about the same dimensions as the one at Copper Cliff, Ont. A few wider furnaces have been built, however.

Recent Installations.—One of the largest copper smelters which have recently been equipped for burning pulverized coal is that of the United Verde Copper Company, at Clarkdale, Arizona. This plant began using pulverized coal in 1919, in place of the more expensive fuel oil which was formerly consumed in enormous quantities.

"A semi-lignite bituminous coal is used, having a maximum heat value of 11,300 B.t.u. and an average of 8 per cent ash content. The pulverizing plant produces 750 tons of fuel daily, when working three 8-hour shifts, and the storage bins at the reverberatory furnaces have a capacity of 65 tons at each furnace, or sufficient for a 12-hours' run. The pressure at the burners does not exceed 8 oz. and the air in the jet supplied by the blowers averages one-fourth of the total volume of air required for complete oxidation of the coal."

Similar conditions as to fuel oil led to the substitution of pulverized coal at the Nevada Consolidated Copper Co., at McGill, Nevada. Eight pulverizing mills of the Bonnot type are used, and the pulverized coal is distributed to the furnaces and burners in suspension in air by the Holbeck low-pressure system.

Fuel Practice in Refining Copper.—Copper matte is treated by the converter process for further concentration of the metal, preparatory to electrolytic refining. The molten matte from the "settler" is poured into a modified Bessemer converter and is purified by blowing air through the molten charge under pressure. The iron and sulphur are oxidized without the use of carbonaceous fuel. The metallic copper is then poured into a refining furnace, or, more usually cast directly into anodes.

Copper Melting.—At Anaconda, "blister" copper from the converters is held molten in so-called refining furnaces, to reduce the oxygen content before casting into anodes. The substitution of pulverized coal for grate firing cut the fuel bill in half.

In firing copper-melting reverberatories with pulverized coal, the burners are merely iron pipes introduced horizontally into the end wall of the furnace. When operated in connection with an eastern electrolytic refinery, two operations are carried out in melting furnaces:

1. *Melting unrefined metal,* including pig copper from western smelters, the remains of anodes from the electrolytic plant, and commercial scrap. Sticks of green timber are forced down into the molten metal to reduce the oxide content. The metal is cast into anodes for the refinery.
2. *Melting refined metal* cathodes for casting into ingots.*

Copper Blast-furnaces.—The latest advance in fuel practice, in the metallurgy of copper and lead, is the use of pulverized coal in blast-furnaces as a substitute for a part of the coke. Since the primary function of the fuel is to produce heat for melting the ore and the fluxing material, this may be accomplished equally well by burning oil or pulverized coal in the voids of the charge. Pulverized coal is introduced into the blast at the tuyeres by means of compressed air ejectors. The amount of coke added to the charge is cut down as much as possible, the function of the coke being to keep the charge open for the passage of the blast.

The earliest experiments on record were made in England a good many years ago but were not attended with success. The art has been developed in the United States within the past

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* The author is indebted to FREDERICK LAIST, metallurgical manager of the Anaconda Copper Co., and E. E. THUM, associate editor, *Chem. Met. Eng.* (and formerly with the Anaconda Co.), for information and assistance in connection with the preceding pages on copper smelting.

five years, as described in the following extracts from papers* by W. L. Wotherspoon† and E. P. Mathewson.

Experiments of Garred.—Garred became interested in the application of pulverized fuel to blast furnaces in 1913, but it was 2 years later when he applied some of his ideas in a practical way, by melting blister copper in a blast furnace, as shown in Fig. 112. The design provided special facilities for combustion, and the tuyeres were so arranged that, in the event of the charge becoming frozen, they would remain clear. During the experiment, over a million pounds of blister copper were melted.

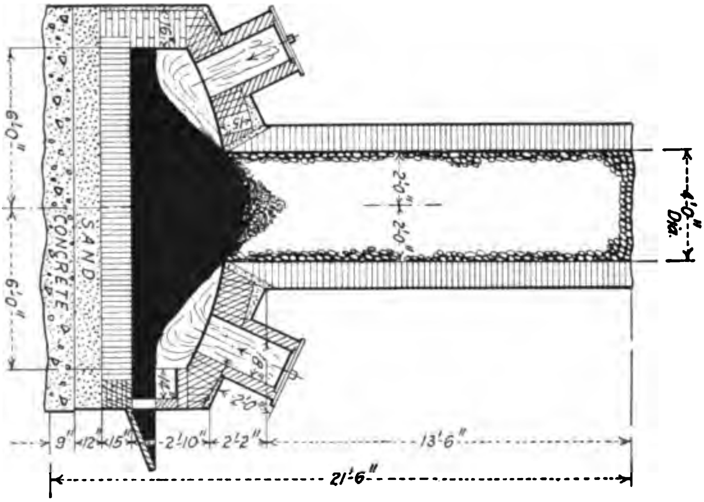

Fig. 112.—Blast-furnace for melting blister copper.

The experiments were particularly interesting, owing to the fact that, with a furnace of 36 in. diameter, handling large angular pieces of blister copper, it was possible to continue the work to the extent described.

In connection with the danger of a charge becoming frozen, it might be mentioned that the furnace was allowed to stand

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* "Application of Pulverized Coal in Blast-furnaces," by E. P. Mathewson and W. L. Wotherspoon, *Trans. Canadian Min. Inst.*, **22**, March, 1919.

"Progress in the Use of Pulverized Fuel in Blast-Furnaces," by W. L. Wotherspoon, *Iron and Steel of Canada*, February, **1920**.

† Gen. Man., Garred-Cavers Corp., 43 Exchange Place, New York.

over a week end, and was then successfully restored to its normal condition in a short time by the use of pulverized fuel.

Experiments at the Tennessee Copper Company's Smelter.—Experiments at the smelter of the Tennessee Copper Co. were decided upon early in 1918, one of the standard blast-furnaces, 22 ft. 6 in. long by 60 in. wide, being used. Ten tuyeres on one side of the furnace were equipped for the use of pulverized fuel, and the first test run of importance was started on April 22 and was continued until May 4, during which period the percentage of coal to the charge was 3.8, as against 5.7 of coke used on the other furnaces during the same period, when operating with a similar charge. The second test run was started on May 9, and continued until May 24, when the percentage of coal used was 3.6; a very small amount of coke was used intermittently.

A third test run was then made, feeding a little coke on the side of the furnace where no coal was fed previously, as it had been found there was a tendency for crusts to form on that side of the furnace.

An analysis of the average ore smelted at Copperhill, Tenn., during 1918, is as follows: Cu, 1.55 per cent; Fe, 34.6; S, 24.6; SiO_2, 20.3; CaO, 4.9; MgO, 2.0; Zn, 1.4; Al_2O_3, 4.3.

The furnace has 27 tuyeres on one side and 24 on the other and the air blast is maintained at 35 to 45 oz. pressure.

Experiments at the International Nickel Company's Smelter at Copper Cliff, Ontario.—Following the work of Garred, already described, the International Nickel Co. decided, in June, 1918, to carry out experiments in the blast-furnace department of its smelter at Copper Cliff, Ontario. It was decided to use one of the standard blast furnaces, which are 25 ft. 6 in. long by 50 in. wide. The furnace bottom is lined with magnesite brick to within 14 in. of the center of the tuyeres; the two lower rows of jackets are cast iron with water-cooled pipes, and the two upper rows of jackets are of the standard water-cooled steel type. The furnace has 48 six-inch tuyeres, 24 on a side, spaced about 12-in. centers. These are connected to a main bustle pipe with 6-in. galvanized branch pipes fitted with canvas sleeves. The bustle pipe is supplied by an offset from the main delivery pipe which feeds seven other furnaces, the normal pressure of air carried at the tuyeres being 23 to 24 oz.

The furnace charge consists mainly of a refractory copper-nickel sulphide ore, a large proportion of which is delivered from the company's roasting plant. The composition of the charge and the average size and analysis of the constituents and products are as follows:

TABLE LXXX

	PERCENTAGE OF CHARGE TO BLAST FURNACE AVERAGE 6 MONTHS
Roast ore	74.8
Raw Creighton	2.8
Raw Crean Hill	8.0
Total ore	85.6
Converter slag	10.2
Converter scrap	3.2
Limestone and quartz	1.0
	100.0

SCREEN TESTS

Roast ore—on 1½ in., per cent	53
Roast ore—on 1 in., per cent	16
Roast ore—through 1 in., per cent	31

Raw Creighton, practically all through ¾ in.

TYPICAL COMPOSITION OF BLAST FURNACE CHARGE AND PRODUCTS

	Cu, Per cent	Ni, Per cent	Fe, Per cent	S, Per cent	SiO_2, Per cent	Al_2O_3, Per cent	CaO, Per cent	MgO, Per cent
Roast ore	1.40	4.10	38.50	11.75	20.25	4.50	2.25	2.50
Raw Creighton ore	1.40	3.90	39.50	23.00	21.00	5.25	2.50	3.00
Raw Crean Hill ore	2.50	1.75	24.00	11.50	32.00	10.00	5.00	5.50
Converter slag	1.00	3.00	47.00	2.40	26.75	3.00	1.25	1.50
Scrap charged	2.25	6.00	42.00	2.00	21.75	2.00	0.75	1.50
Limestone	....	.....	1.00	.....	2.50	.....	52.75	1.10
Quartz	....	.....	3.00	.....	91.00	2.90	1.00	1.00
Bl. Fur. Matte	5.85	14.35	48.40	26.25	(6 mon	ths ave	rage)	
Bl. Fur. slag	0.16	0.32	40.90	1.65	33.15	6.50	3.70	2.50

The furnace, under normal conditions of smelting, treats about 500 tons of charge a day, using 60 tons of coke; the average coke consumption for six months being 12.5 per cent of the charge.

Regarding air conditions, only approximate estimates were available, owing to the whole of the blast furnace plant being supplied from a central blower installation. General observations indicated that the furnace charge is kept about seven feet deep, and the smelting zone is from two to three feet above the tuyeres. Blow holes form quickly after a fresh charge, but the amount of dust made is about normal, *viz.*, 1.5 to 2.0 per cent. to the ore.

The tuyeres require punching regularly, the method being to remove the tuyere cap and, by introducing a rod, to ease the ore in the vicinity of the tuyere. It was usual, when cleaning these tuyeres, for some loose ore to be blown out on the furnace floor in a condition which indicated that the ore close to the tuyeres had not been strongly heated. Through the tuyeres, the charge appeared black and usually there was no appearance of fire until near the middle of the furnace.

The usual practice is to make up a furnace charge consisting of certain proportions of roasted ores, green ore, by-products, such as converter slags, and coke—all being dumped into the top of the furnace from small cars in such a way as to give an even distribution in the body of the furnace. Under these conditions of intermittent charges of the fuel, the regularity of its distribution is not easily obtained.

Arrangements for conducting the experiments were greatly facilitated because the company had utilized pulverized coal in reverberatory furnaces since 1911.

In commencing the experiments, the air blast for the combustion of the coal and for smelting was furnished in the regular way under normal operating pressure, and the pulverized coal was introduced directly into the blast before entering the tuyere. It was found that the coal could be introduced very rapidly in this way while the furnace had its regular charge of coke and ore; but when the coke was cut below 50 per cent. of normal, it was found that the tuyeres became closed, coal dust would lodge in the tuyere pipes, and a certain quantity would find its way into the bustle pipe, causing trouble at any leaky joint, thus rendering the condition around the furnace more or less dangerous. At this time the joints between the furnace jackets and the tuyeres were not as tight as they should be, and there was considerable leakage of coal dust. Later on, the coal was introduced to the blast by means of an ejector like that used by Cavers at the Tennessee Copper Co.

During this stage of the experiments, the main troubles were at the tuyeres, which required regular punching, and there was some leakage of coal. The coal was applied to only half the tuyeres on each side of the furnace, being introduced to alternate tuyeres, those on the front of the furnace being staggered in relationship to those at the back. The experiment was then made of introducing the coal between and slightly above the tuyeres, by boring a hole through the jacket and connecting to these the coal supply pipe from the ejectors at the screw feeds, thus introducing a dense mixture of coal and air into the furnace independent of the main air supply. This was found to be a clean method and a test was made over a period of eight days. During this time the coke was reduced from 12 per cent. to about 6 per cent., with promising results; the most important and necessary condition still being that of keeping the tuyeres open. It was observed that the small openings (1½-in. pipe) through which the coal was introduced into the furnace required very little punching, the main trouble being with the large tuyeres; and by observation through the Dyblie valve, the combustion and the smelting of the ore in the furnace could be seen in operation.

Influence on Operating Conditions and Costs.—It is a foregone conclusion that the characteristics of the charge will have an important bearing on the results obtained. At Tennessee the charge consists of run-of-mine ore and quartz in large pieces, with a high percentage of sulphur, and melting conditions that call for relatively small quantities of fuel. At Copper Cliff, the ore is comparatively fine, over 74 per cent. of the charge coming from the roasting beds from which it is reclaimed and handled two or three times, and the final sulphur content does not much exceed 12 per cent.

There are some blast-furnaces operating in conjunction with reverberatory furnaces, where the blast-furnace charge is favorable for easy smelting conditions, due to the slags and other by-products being treated therein. It is generally believed by those conversant with the experiments that successful work at Copper Cliff can assuredly be followed by successful work in a large proportion of the blast-furnaces smelting non-ferrous ores elsewhere.

Regarding blow holes in the charge, it appears that these should be less when utilizing pulverized fuel than under normal operating conditions, as segregations of the coke are, to a large extent, responsible for the blow holes. For the same reason, beneficial results might also be anticipated regarding dust losses.

It is often stated that large pieces of incandescent coke are necessary in the charge to support the burden. This may be so under certain conditions, but the experiments indicate that it is not essential in smelting copper sulphide ores, and it is not expected to be a matter of great moment when treating other non-ferrous ores.

Another point of great importance is the effect of the Garred-Cavers process on the tuyeres and the amount of tuyere punching. Tuyere punching, under normal conditions, entails a good deal of hard labor, and it is the opinion that the conditions in this connection will be greatly improved. The moisture content in the charge may be high without causing trouble; during the experiments several charges of wet fines, the clean-up from storage bins, having been handled without trouble.

In blast furnace smelting of copper ores, the ash content of the fuel is of minor importance, and the more erosion in a furnace charge the greater the efficiency, so that these two factors connected with the use of pulverized coal, which are discussed so freely in connection with other furnace applications, are here of little significance. The influence on power costs should be favorable, owing to the increased efficiency in the furnace and the possibilities of more regular charge reducing the wastage of air. The amount of power used for applying the coal at the furnace is small, being confined to the feeders and other apparatus, such as ejectors, etc. The air supply will naturally vary according to the character of the furnace charge and the height of the column that is found to be advisable. The present work has been carried on with the same air pressure and the same height of charge as is usually employed at these smelters; but if higher pressures are utilized, it is anticipated that the additional cost of power will be more than met by the increased efficiency in the smelting operation.

The introduction of the fuel at the tuyeres gives considerable relief on the charge floor of the furnace, and in a large smelter should have favorable effects on the cost of tramming; the coke being usually handled in cars or other mechanical devices, from storage bins, and this requires an appreciable amount of labor, power and equipment.

The most important influence on operating costs is in connection with the fuel utilized, the normal practice being to use coke alone, whereas these experiments show that coke can be replaced, to a large extent, by pulverized coal. The relative costs of coal and coke vary a great deal, but, on the average, coke may be stated to cost twice as much as coal delivered at the smelters. It is only necessary to refer to the fuel conditions in Canada to appreciate this phase of the problem. For instance, the International Nickel Co. of Canada, Ltd., consumed in connection with its blast furnace plant at Copper Cliff, during the last few years, about 300 tons of coke per day, the average cost of this product being (during the fiscal year of 1915–16) $6.25 per ton. The price of high-grade bituminous coal, as used in connection with reverberatory furnaces, had a corresponding cost of $3.50 per ton of slack. Up to the present, high-grade bituminous coal has been used in the experiments. The average analyses of this coal during the month of August, 1918, which average may be said to be fairly representative was: carbon, 51.85 per cent; volatile matter, 36.10 per cent; ash, 12.05 per cent; and sulphur, 3.28 per cent—fineness, 93 to 94 per cent to pass a 100-mesh screen, and 75 to 85 per cent to pass a 200-mesh screen. It will undoubtedly be possible, however, to develop the use of a large variety of pulverized fuels for blast furnace operations, as has been the case with boilers and other types of furnaces. Lignite will be suitable in many localities, among which are certain portions of Canada, Mexico and Burma.

Recent Tests with Canadian Ores.—In his second article (February, 1920), Wotherspoon gives the results of comparative tests in the smelting of copper-nickel ores which are summarized in Table LXXXI. The two furnaces were identical in size and were operated with the same blast pressure and furnace charge.

TABLE LXXXI

	No. 7 Furnace' Coal and Coke	No. 8 Furnace, Coke Only
Ore, tons	2,802	3,023
Charge, tons	3,013	3,188
Coke, tons	225	411
Coal, tons	192	
Total fuel, tons	417—13.8 per cent	411—12.9 per cent
Fuel cost	$4,869.00	$6,370.00
Fuel cost, per ton of ore	1.74	2.11

The cost of pulverizing the coal and the extra labor connected with the coal feeders would be about $0.07 per ton of ore, which would make the fuel cost per ton of ore for No. 7 furnace, operated with the fuel combination, $1.81.

The charge of a furnace consists of the ore plus fluxes and by-products, such as slags, etc., but does not include coal and coke. The quantity of this material used in this case is a very small percentage of the furnace charge.

New Furnace Design.—Figure 112 shows the latest type of blast-furnace which has been designed for the use of pulverized fuel by the Garred-Cavers Corporation. The design includes a special furnace jacket, in which is incorporated a small combustion chamber to which the tuyere is fitted. Figures 113*a* and 113*b* illustrate the vortex tuyere and a small combustion chamber or enlarged tuyere, together with the method of applying this to a blast furnace. These have been designed to guarantee the full pressure of air at each tuyere and to act as an igniter for the coal as it enters the furnace.

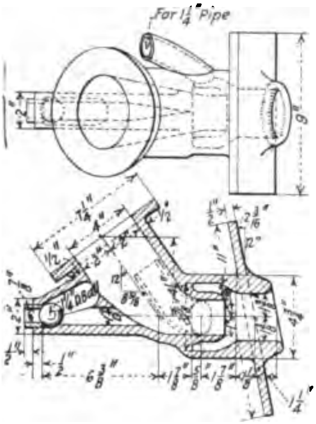

FIG. 113*a*.—Vortex tuyere and adaptations of tuyere to form small combustion chamber.

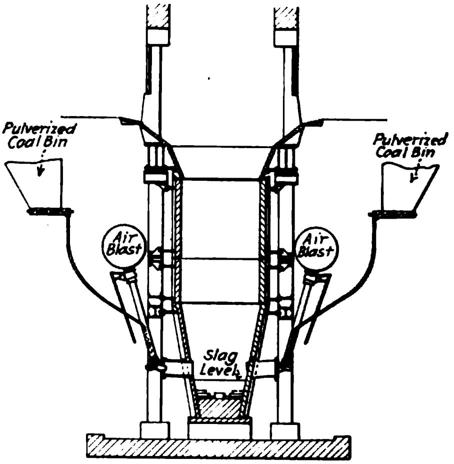

FIG. 113*b*.—Method of applying pulverized coal to blast furnace.

The nozzle shape of the air duct through the tuyere holds the air pressure at this point about the same as the blower (provided the blast main is large enough). This brings within the tuyere primary and secondary pressures; the primary being that of the blower side of nozzle and the secondary the furnace side of nozzle. This is found necessary to take care of the change of conditions in the furnace caused by blow holes and sliding and settling of the charge. Any small obstruction to a single tuyere will be overcome immediately by the pressure building up and relieving itself. Thus we have a safety device against backward flow of coal or back blast into tuyere pipe. The ball valve furnishes a means of punching the tuyeres without coal escaping into the room, as it is so arranged that the rod passes through the clean air nozzle, through the vortex chamber where the coal is admitted and from there into the furnace. The air pressure of the furnace always being less than in the nozzle, the coal flows into the furnace, allowing only clean air to come out around the punch rod. The small combustion chamber is lined with a highly refractory substance and is kept white-hot by the coal igniting in it. This serves a double purpose, *i.e.*, preheating the air before it enters or comes in contact with the charge and holding the smelting zone near the tuyere. The combination of these points should make a blow torch action at each tuyere, maintaining rapid smelting at this part of the furnace.

New Installations.—This development has aroused great interest among metallurgists in many parts of the world, as the fuel conditions existing at many smelters have been such as to interfere greatly with production, and the substitution of pulverized coal for a considerable portion of the coke offers many advantages.

The American Smelting and Refining Company, at its Garfield plant, is using a standard blast furnace for trying out the process in the smelting of copper ores, the percentage of fuel replaced also being about 30 per cent. These results are being obtained with normal blast pressures with practically no modifications to the standard blast-furnace.

The output and general operation of this furnace are as good as those of the other furnaces run under normal conditions. The careful records kept of the experiments performed at this plant are found to be encouraging for the continuance of the process.

Recently experiments have been carried out with the process at the smelter of the Cerro de Pasco Copper Corp. in Peru; the results being such that it is expected, under the conditions existing there, that 50 per cent. of the coke will be replaced by pulverized coal, obtained from the Corporation's own mine in that district. This organization has designs for a complete new smelter, which will consist of blast-furnaces and reverberatory furnaces, in both of which pulverized coal will be used.

To W. J. Hamilton, Consulting Engineer of the Cerro de Pasco Copper Corp., should be given credit for the encouraging results obtained from tests made at the plant, and under his recommend dation the Corp. has contracted with the Garred-Cavers Corp. for a license to use the process.

Lead Smelting

More recently the process has been applied to the smelting of lead ores. At the Midvale, Utah, plant of the United States Smelting, Refining and Mining Co., pulverized coal has been used in a lead blast furnace for over a year. It replaced between one-fourth and one-third of the coke. A method has been developed which gives the absolute control which is necessary for lead smelting and, under certain conditions, the metallurgical work is better with coal. Extra labor is needed, probably due to the preparation of the coal on a small scale, and the tonnage has so far been reduced about 6 per cent. The net results, however, show a good profit.

E. H. Hamilton, of this plant, is an enthusiastic supporter of pulverized coal in blast-furnaces and should be given credit for pioneer work in lead smelting. Experimental work carried on under his supervision has met with such success that he feels there is no doubt of it being adapted to lead smelting.

Possibilities for Complete Substitution of Pulverized Coal for Coke.—One copper blast furnace has been operated experimentally with pulverized coal only as fuel. This may be possible in the case of ores which allow the charge to remain sufficiently open. So far most of the experiments have been carried on at standard blast pressures. It has been mentioned that the use of higher pressures will increase the efficiency of the furnace. It is also expected that it may render possible the elimination of the coke and the complete substitution of pulverized coal as fuel in blast furnaces for smelting non-ferrous metal ores.

POSSIBILITIES IN THE IRON BLAST FURNACE

In these experiments it not only has been established that finely-divided fuel can be burned in the small spaces between the ores in a shaft furnace, but beneath a molten mass of slag, ore, or metal, with either a reducing or oxidizing flame. Coal does not require a certain definite space per pound to satisfy combustion, but, on the contrary, combustion can be had in a confined space under pressure.

It would appear that, with the successful application of this process to a variety of non-ferrous ores, the chances of success in extending the process to the iron industry are deserving of consideration. It is admitted that the chemical problems in the smelting of different ores vary considerably, this being particularly so in the iron blast furnace; but it is also evident that combustion of pulverized coal can be controlled so as to give results that might be of considerable advantage. If only a small percentage of the coke were replaced in the iron blast furnace, the benefits obtainable would be great from an economic viewpoint.

Zinc and Tin

Pulverized coal is being used in a few plants for smelting and roasting zinc ores in reverberatory furnaces. One zinc smelting furnace is 57 ft. long, outside, by 18 ft. 9 in. wide and 14 ft. high. This is located at the River Smelting & Refining Co., at Florence, Col. The matte contains copper, zinc, gold and silver. This fuel is also used in firing a few tin furnaces of the reverberatory type.

Assay Furnaces

The operations previously considered are on a large scale. Pulverized coal, however, is sometimes used on a small scale for firing assay furnaces, principally in connection with the assaying of Colorado ores containing silver and gold. Higher temperatures are obtainable in muffle furnaces than are possible with oil or gas firing. Pulverized coal firing is also claimed to be cheaper.

The equipment used is especially adapted to small furnaces, and the preparation and firing are done on what is commonly known as the "unit system." A small McCool pulverizer is mounted directly on the side of a furnace which is supported on legs. This is fed with undried screenings from slack coal or lignite. The air for combustion is drawn through the pulverizer and entrains the finished particles of pulverized coal, carrying them directly into the furnace. A larger pulverizer of the same type is shown in Fig. 114 and will be described in a later section. This self-contained equipment, in its smallest size, is capable of preparing and burning from 15 to 25 lb. of coal per hour.

Chemical Reactions in Pulverized Coal Flames

Various suggestions have been made for carrying on chemical reactions in pulverized coal flames. The raw mineral would be pulverized, mixed and then fired in suspension with the fuel.

One experimenter reports some preliminary success. The successful development of such processes may render possible the substitution of coal for coke or other high-grade fuels.

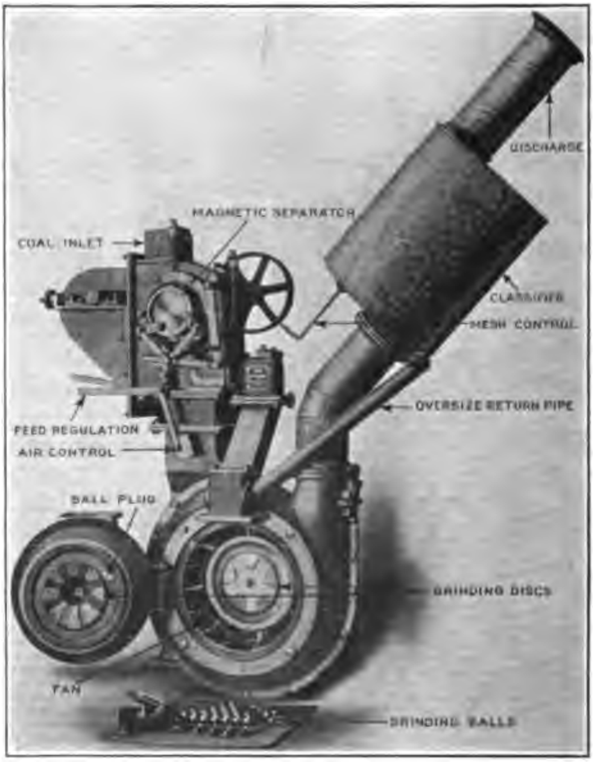

Fig. 114.—McCool disk pulverizer.

Consumption of Pulverized Coal in Various Industries

According to recent estimates made by the Fuller Engineering Co., the total quantity of coal burned in pulverized form in various industries is as follows:

Cement industry	between 5 and 6 million tons per year.
Iron and steel industry	between 2 and 3 million tons per year.
Copper industry	between 2 and 3 million tons per year.
For steam and other purposes	the balance.
Total consumption	about 12 million tons per year.

BOOKS AND PAMPHLETS

For further information regarding the use of pulverized coal for industrial heating, the following literature may be consulted:

"Powdered Coal as a Fuel," by C. F. HERINGTON; 324 pages, including bibliography of 20 pages, compiled by the Engineering Societies' library. D. Van Nostrand Co., New York, 1920. Second Edition.

"Pulverized Coal Systems in America," by L. C. HARVEY; Fuel Research Board *Special Report* No. 1; 65 pages, including bibliography of 7 pages, London, 1919.

"The Use of Pulverized Coal," with special reference to its application in metallurgy, by L. C. HARVEY; 70 pages. Presented before the Iron and Steel Institute, May 8 and 9, 1919. Reprinted by Spottiswoode, Ballentyne & Co., Ltd., London.

"Pulverized Fuel, its Use and Possibilities," by W. J. DICK; 57 pages. Commission of Conservation of Canada, Ottawa, 1919.

MECHANICAL PREPARATION OF COAL

Crushing, Drying, Pulverizing, Cleaning

The mechanical preparation of finely divided fuels for the various uses reviewed in this Chapter may be summarized as follows:

1. *Granulation for distillation processes.* Coal is sometimes granulated in a hammer-mill to prepare it for distillation at low temperature, as well as for coking in by-product ovens. In the case of coals with a high moisture content, drying may be necessary as a further preparation for distillation at low temperature.

2. *Granulation for pneumatic firing* over a grate. This may also be done in a hammer-mill and the product need not be dried if it is to be used immediately. Where it is to be stored for any length of time, or handled in a mass by pneumatic conveying methods, it should be dried.

3. *Pulverizing for burning in suspension.* This preparation usually involves a preliminary crushing and drying, followed by a final grinding to the required degree of fineness. There are two general systems in use for preparing and burning pulverized coal, which are usually distinguished by the names "storage" and "unit" systems.

REVIEW OF EQUIPMENT

The leading types of American commercial equipment, together with the leading methods, will be considered under appropriate headings.

Granulation and Crushing.—Two general types of crushing machinery are used for crushing or granulating coal:

1. *Hammer-mills* are high-speed machines which usually carry from four to six sets of hammers pivoted to swing from a built up hub mounted on the main shaft. These pulverize the coal by impact and reduce it to whatever size the grid is set for. The product may range from crushed coal of ½ in. and under, down to a granulated coal, of ⅛ in. and under, while some machines will reduce bituminous coal to a 20-mesh product. A considerable amount of dust is created in the process, which is advantageous for the pneumatic firing of coal over a grate, but which is objectionable for some other applications.

2. *Crushing rolls* are commonly built in two general types: *single* rolls and *double* rolls. The single-roll crushers are generally used for coarse crushing, and the double rolls for fine crushing, where it is desirable to keep down the dust content in the product to a minimum.

The first step in the preparation of pulverized fuel is to crush the run-of-mine coal to such a size that the largest lumps will pass through a ring from ⅜ to 1¼ in. in diameter, according to the size and type of the pulverizer in which the final grinding is to be done. Where slack coal or screenings are available, and of the proper size, the crushing operation is omitted.

The single-roll crusher is generally used, the Jeffrey being a common type in coal-pulverizing plants. In this machine the coal is crushed between a toothed roll and a concave breaker plate. The roll is provided with a large number of short manganese-steel teeth, which do the final crushing, and with a smaller number of long teeth which catch hold of the lumps which are too large to drop into the cavity between the roll and the breaker plate, and pinch them against the top of the plate. This preliminary breaking reduces the lumps to a size which allows the short teeth to catch hold. The long teeth also act as feeders for the smaller material.

In some plants the coal is put through two sets of roll crushers in series. A single-roll crusher reduces the run of mine coal to 3 or 4 in. lumps, while a double-roll crusher reduces it to ⅜-in. lumps and under.

The handling and conveying of coal from the storage pile to the milling plant is effected by the various mechanical types of conveyors and elevators.

Pneumatic Conveying and Crushing.—An alternative method for conveying coal has been developed by the Pneumatic Elevator and Conveyor Company, of Philadelphia. Pneumatic conveying has been used for many kinds of lump materials, such as grain, ashes, coke breeze, and various minerals. Coal can be handled pneumatically as readily as other materials of similar size. The smaller sizes of coal should be more readily fed to the conveyor pipe. Run-of-mine coal can be conveyed through pipe of sufficient size to pass the largest lumps. Where ashes and other hard materials have been conveyed pneumatically, there has often been a tendency for the pipe elbows to wear out from abrasion. This difficulty has been overcome by the use of air cushions, formed by jets of air admitted through suitably located openings, which prevent the material from coming in contact with the metal.

The velocities used in this system are quite high and it has been found that the slippage of the material allows the air to effect a considerable degree of drying, probably by the atomization of the surface moisture. It has been found that wet sand is dried quite thoroughly during pneumatic conveying. The conveying of fine coal by this method should effect a partial drying and a reduction of surface moisture, including the variable quantities resulting from exposure to weather. This should relieve the dryer of a part of its work by reducing the moisture content to a more uniform percentage.

Lump coal may be broken in the process of conveying by utilizing the inertia of the lumps by allowing them to strike upon a breaker plate as they enter the receiving tank.

In nearly every coal-pulverizing plant, there is more or less fine coal dust deposited on the floor, the pulverizing machinery, girders and window sills of the building. If, for any reason, this dust should be raised into a cloud and then come in contact with an open flame, it is probable that an explosion would occur which would wreck the plant. In fact, there was an actual occurrence of this nature in a coal-pulverizing plant in which a primary explosion happened in the pulverizer and raised the dust in the building into a cloud, ignited it, and the resulting explosion caused considerable damage to the building, as well as costing loss of life.

Every effort should be made to prevent any accumulation of dust in the building that houses the pulverizing apparatus.

Certain manufacturing plants, in which explosive dust is prevalent, have installed vacuum cleaners to keep the buildings free from dangerous quantities of explosive dusts, and such systems have been in use for many years in Northern France and Germany in connection with coal-screening plants. This would not be impracticable in a coal-pulverizing plant. Indeed vacuum cleaners will probably be required by the fire underwriters before long. The recovered dust could be delivered to the pulverized coal bin and used in the furnaces.

Fuel Handling in the Milling Plant.—The crushed coal is usually raised from a pit to the top of a one-story building by means of a bucket elevator and then fed by gravity through a storage bin to the dryer. A second elevator lifts the dried coal to a second bin, from which it is fed by gravity to the pulverizer. If the latter is a screen type mill, the pulverized coal is sometimes raised by a third elevator to the conveyor. When an air separation mill is used, it is carried upward in suspension to a cyclone separator.

In a milling plant at the Erie, Pa., works of the General Electric Co., a single elevator carries the coal from the crusher pit to a bin in the top of a two-story building, from which it is fed by gravity through the dryer and pulverizer in succession. As the latter is an air separation mill, only a single mechanical elevator is required.

With pneumatic conveying of the raw coal from the storage pile to the milling plant, and pneumatic conveying of the pulverized coal from the mill, the bucket elevator could be eliminated. Pneumatic mass conveying methods are now available for handling the product of a screen type mill.* The installation of the dryer on the second floor requires a more expensive building, but simplifies the handling of the fuel and reduces the cost of maintaining the milling plant.

The various ranks and types of coal differ markedly in their avidity for oxygen at ordinary temperatures. When in a finely divided state, all coals slowly absorb oxygen and this may account for the fact that freshly mined coal is often more subject to spontaneous ignition than coal which has had time to become saturated by the adsorption of gases on the surfaces of the particles. Some coals of low rank, however, are rendered very susceptible to spontaneous ignition when the pulverized material

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* The Fuller-Kinyon system is described on page 641.

is exposed to the air for a sufficient time to become partially oxidized.

This has been noticed in the case of certain coals from New Mexico which are used by the United Verde Copper Co., at Clarkdale, Ariz. If dust is allowed to accumulate anywhere inside a building or pulverizer mill, and then to lie for 2 or 3 days, the least amount of heat applied will cause it to ignite and burn. It was found necessary to see that all pockets in the mill and its air circulating system are cleaned out when the mill is shut down. The coal used is subject to spontaneous ignition, even in lump form, and it is stored on the ground in water-tight bunkers which are so constructed as to allow of flooding the coal daily. With proper precautions, the pulverized coal is handled with entire safety.*

The Storage and Unit Systems.—1. *The storage system* is by far the most common. The preparation of the coal is centralized and may be carried on continuously, the finished product being stored in bins until required. This system is especially adapted to large installations where the daily consumption is at least 50 or 100 tons.

2. *The unit system* is applicable in smaller plants and for firing isolated furnaces or boilers. Crushed or slack coal is used, but it is not always dried before pulverizing. The air for combustion is furnished by a fan, which is built into the pulverizer, and which draws at least a large part of the air through the pulverizer to entrain the finished product and carry it in suspension to the furnace. The fuel is prepared as needed and no provision is made for storing the fuel in pulverized form. This simplifies the handling of the fuel after pulverizing, but does not eliminate the conveying and handling of the crushed coal from the storage pile to the furnace.

Drying.—The object of drying the coal before pulverizing is to secure the following advantages:

1. *To enable the pulverizer to operate at maximum capacity.* Drying renders the coal more brittle, while moisture tends to make the particles adhere together so that the fine material cushions the blows. Thus moist coal tends to choke the machine and the finished material is not removed promptly.

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* "Experience with Powdered Coal in Arizona," by J. B. JOHNSON, *Electrical World*, **78**, 1121 (Dec. 3, 1921).

2. *To Enable the Coal to be Readily Handled.*—Dry pulverized coal has semi-fluid properties; it flows easily and can be conveyed through pipes or conduits. Moist coal tends to arch and hang in the bins.

3. *To avoid spontaneous ignition* during storage, the coal must be cool and dry when it goes into the bin.

4. *To obtain maximum flame temperature* during combustion, and to obtain uniform furnace conditions. Higher furnace efficiency is obtained as an offset to the fuel consumed in the dryer furnace. This factor is usually of less practical importance than the three factors previously mentioned. Undried pulverized coal has been burned in boiler furnaces with as high an efficiency as dried coal, provided the heat required for the evaporation of the additional moisture in the undried coal be credited against it.

Moisture Content.—The maximum content of moisture which is permissible in pulverized fuel varies with the physical characteristics of the fuel. With bituminous coals of high rank the usual practice is to dry the coal to a moisture content of between 0.5 and 1.0 per cent, which allows a margin for absorption of atmospheric moisture.

In a few coal milling plants the coal is not dried before pulverizing. The cases where drying can be dispensed with, however, are exceptional, as in the case of the Allegheny Steel Company, at Brackenridge, Pa., where coal is obtained from a nearby mine owned by the company. In this case the moisture content of the raw coal is only about 1 per cent.

Experimental work conducted at the University of Illinois has contributed some valuable data in regard to the percentages of moisture allowable in fuels of various ranks. W. J. Risley, Jr., states* that "under the difficulties in handling and distribution caused by moisture, we might add that moisture is one of the chief accelerators of spontaneous heating."

His experiments "confirmed the recommendations of many manufacturers of pulverizing machinery, that the coal be as dry as possible to give the best results in pulverizing and burning. Typical samples of crushed bituminous coal, lignite, and peat were each subdivided into portions differing only in moisture content. Each portion was given a certain amount of pulverizing in the same mill, and the percentage product passing through

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* *Power*, August 23, 1921; p. 301.

a 200-mesh screen was then measured. With both Pittsburgh and Kentucky bituminous coals the most advantageous moisture content for pulvering was about 1 per cent; below that nothing was gained, while above that the cost of pulverizing rose rapidly with increasing moisture content. In the case of bituminous coal from Illinois having a much wider range of moisture content, 1.8 to 2 per cent seemed to be the most economical moisture content. If the coal is dried more than this, it evidently becomes harder, because the cost of pulverizing increases. If the moisture content is above this point, the pulverizing cost rises rapidly with increasing moisture. The most economical moisture content for North Dakota lignite was found to be in the neighborhood of 7.5 per cent, and for peat about 9.5 to 10 per cent. Above these figures, pulverizing costs increased rapidly.

"Another factor affects the extent to which drying can be economically carried. The major portion of the moisture content of any fuel seems to be surface or free moisture, while the small remainder might be called inherent moisture. The former is easily driven off, the latter with difficulty. For instance, any drying of lignite on a commercial scale below 5 or 6 per cent is quite expensive, indicating that, before this point is reached, the free moisture has all been driven off and a start has been made on the more obstinate inherent moisture. The tests seemed to indicate that in each case the most economical moisture content for pulverizing was also the point beyond which the drying itself becomes disproportionately expensive."

When solid fuels are dried below the point at which their hygroscopic moisture is in equilibrium with the atmospheric moisture, they tend to absorb moisture if left exposed to the atmosphere. Pulverized coal, however, owing to the minuteness of its particles, is somewhat water-repellent and can be wetted only with difficulty. In a certain instance where pulverized semi-bituminous coal was left in bags on a wharf, exposed to the elements for many weeks, the moisture content rose to about 2.3 per cent, which was probably the equilibrium point for that particular coal.

When peat or some kinds of lignite, however, are dried below their equilibrium point, they will readily reabsorb moisture from the atmosphere up to a content of between 15 and 20 per cent,* according to the humidity. A Texas lignite was dried to a mois-

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* C. A. Davis, "The Uses of Peat," *U. S. Bureau of Mines, Bull.* **16.**

ture content of about 17 per cent. in a rotary dryer.* It was then pulverized in a Fuller mill and no difficulty was experienced with the pulverizer, which functioned just as well as with dry bituminous coal.

According to Haanel,† peat should be dried to a moisture content of not more than 13 per cent. for pulverizing and burning. This is more than can be accomplisyed by the wet carbonizing process (Chap. VI) or by air-drying in a moist climate. Hence the final drying must usually be done with artificial heat.

Methods for Drying Fuel.—There are two general methods of importance used for drying coal and other materials by heat accompanied by mechanical agitation, viz.:

1. *The rotary dryer* consists of a long cylindrical steel drum which rotates slowly about an axis which has a slight inclination with respect to the horizontal. Crushed coal is fed into the upper end and travels gradually to the lower end. Lifting plates are mounted on the inside of the shell and these pick up the coal and cascade it down through a current of hot furnace gases.

2. *The tower dryer* is an alternative method which is seldom used for drying coal, but which has the merit of simplicity. It may be used in connection with hot flue gas from the main furnaces, or be separately fired. The material is showered down through a vertical chamber while the hot gases rise through it When furnace flue gas is used as a source of heat, the tower may be located alongside a stack, and economy in the use of the available heat is of minor importance.

Commercial Types of Dryers.—There are many makes of rotary dryers on the American market, and about a half-dozen of these are used for drying coal. They may be divided broadly into two types, according to the method of applying the heat:

1. *Internally heated* from a furnace located at one end of the drum. The firing may be either "direct" or "indirect."

2. *Externally and internally heated* from a furnace located under the drum. The firing is indirect as the gases from the furnace first pass over the outside of the drum and lose their initial temperature, and then through the length of the drum.

Internally Heated Dryers.—The *Bonnet* dryer is of the direct-fired type and consists of a very long drum with a furnace

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* J. Harrington, *Gen. Elec. Rev.*, October, **1917**, 776 (7 per cent., as mentioned on p. 771, is a misprint).

† *J. Am. Peat Soc.*, April, **1921**.

located at the lower end where the coal is discharged. Thus the coal and the hot gases pass through the drum on the counterflow principle. The temperature at the furnace end is kept below the ignition-point of the coal by diluting the hot gases with a supply of air admitted above the grate. This air is warmed in passing over the fuel bed and the drying is done by a large volume of warm air rather than by a smaller volume of gases at a higher temperature.

There is no restricted area and the large volume of gases pass through the drum at a low velocity with natural draft at the stack. This low velocity avoids the entrainment of coal dust and its loss up the stack.

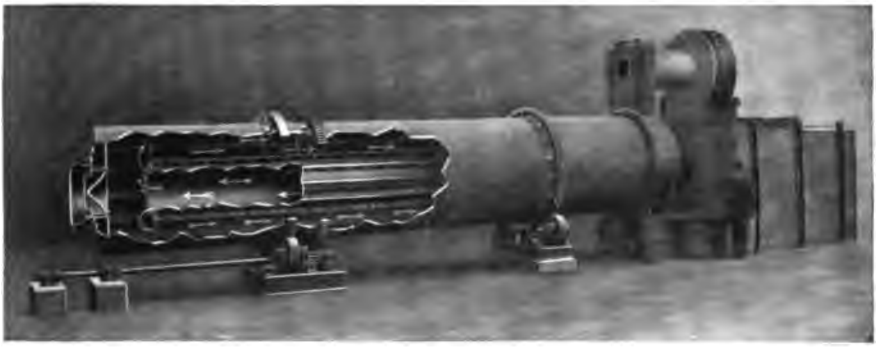

Fig. 115.—Ruggle-Coles rotary dryer.

The Ruggles-Coles dryer (Fig. 115) is of the indirect-fired type and contains an inner drum which is practically an extension of the combustion chamber. The hot gases from the furnace are diluted with sufficient excess air to reduce their temperature to about 760°C. (1,400°F.) before they enter the inner drum. The coal is fed down through the annular space between the two drums and is heated by contact with the wall of the inner drum. This cools the gases to about 120°C. (250°F.) by the time they reach the lower end of the drum. They return through the annular space in contact with the coal and are further cooled to about 38°C. (100°F.), by the time they return to the upper end, which renders it possible to handle them with an exhaust fan. The average temperature of the gases, while in contact with the coal, is only about 80°C. (175°F.), and their volume is so reduced that the velocity is less than 300 ft. per minute at the upper end of the drum, so that comparatively little dust is carried off.

Seven tests on the drying of various materials in Ruggles-Coles dryers showed an average thermal efficiency of 83.2 per cent. This dryer is quite frequently used in coal-milling plants and is sometimes fired with pulverized coal.

The Buckeye "Type-B" dryer is fired through an inner drum which only extends half way through the length of the outer drum. The furnace is located at the lower end, at which the coal is discharged from the annular space between the drums, the final stages of the drying being effected by indirect heat from the inner drum. The wet coal is fed into the upper end of the large drum and the initial stage of the drying is effected by direct contact with the hot gases beyond the end of the inner drum. The gases make only a single pass through the dryer and are exhausted from the upper end by a fan.

It is claimed that this dryer does not usually require any dust-collecting equipment, as there is only a slight current of gases passing through the material during the final drying stage to carry off the evaporated moisture through an auxiliary flue at the lower end. This dryer is built in 12 sizes, ranging from 4 ft. in diameter by 25 ft. long, to 8 ft. by 60 ft. The furnace may be adapted to hand- or stoker-firing or for burning pulverized fuel.

The Allis-Chalmers double-tube dryer is made up of two shells arranged concentrically. The inner shell, which carries the material to be dried, extends some distance beyond the main shell at the upper (feed) end, and to within about 2 ft. of the lower (discharge) end. It is attached to the outer shell by means of flexible connections permitting the free movement necessary to take care of uneven expansion in the two shells. The furnace is located at the upper end of the dryer. A simple air seal is provided at the point where the outer shell enters the furnace as well as at the point where the inner tube passes through the brickwork. The coal to be dried is fed into the inner tube, and, due to combined action of the lifters, and the slope or "pitch" of the shell, works its way to the lower end, where it drops through the spout in the stationary discharge end hood. The furnace gases enter the space between the two shells, and, after heating the coal indirectly, pass into the inner tube and directly over the coal. By means of an exhauster connected to the feed end of the inner tube, they are drawn through the "showering" mass of coal and discharged into a stack.

Externally and Internally-heated Dryers.—In the four makes of dryers to be described under this heading, the steel drum is either wholly or partially enclosed in an external brick oven. The hot gases from the furnace pass through the oven and over the outer surface of the drum until they have become partially cooled by giving up their heat indirectly to the material within the single shell. Then they enter the drum at the lower, or discharge, end (except in the Cummers' dryer), and traverse its entire length, passing through the showering coal. The liability of igniting the coal is avoided by the low temperature of the gases as they enter the drum.

The Fuller-Lehigh dryer is illustrated in Figs. 164 and 169. The furnace is located below the drum, near the upper end, and under a perforated arch. The oven surrounds only the middle portion of the drum. In recent installations it is usually fired with pulverized coal.

The Kennedy-Van Saun dryer has the greater part of its drum surrounded by a brick chamber, leaving only short protruding ends which carry the gear and rollers. The firebox is located in a Dutch oven and discharges the hot gases directly under the upper end of the drum, where they heat the moist coal rapidly, and soon after it enters the drum. The hot gases then travel over the length of the drum, and are given a spiral motion by suitable baffle walls in the chamber, until they reach a flue which conducts them to the lower end of the drum. The same company designs tower dryers.

The Allis-Chalmers "Ebro type" dryer has the furnace located under the middle of the drum, but beneath an arch which deflects the hot gases and discharges them under the upper end of the drum. In other respects it is somewhat similar to the last one.

The Cummers dryer has the drum enclosed in a brick chamber for almost its entire length. The firebox is located outside the chamber and discharges the hot gases, under and through a perforated arch, below the upper end of the drum. The distinctive feature of this dryer is that the drum is perforated with holes, 10 in. in diameter, which are scattered along its length. These are fitted with angle hoods on the inside, which open toward the upper end of the drum, and which allow about three-fourths of the warm gases to enter the drum at these points without allowing coal to fall out. The remaining fourth of the gases travel over the drum and enter at the lower end. Cool air is admitted through adjustable openings in the bottom of the brick side walls, at several points along their length, in order to dilute and cool the gases. Thus, the part of the gases which enter the lower end of the drum are relatively cool and allow the coal to be discharged at a low temperature. Also, the velocity of this portion of the gases will be very low and a minimum quantity of dry dust is entrained. A high-thermal efficiency is claimed for this dryer, and it has been used very successfully in coal-milling plants.

Retrieving Dust.—Many dryer installations are equipped with suction fans and cyclone separators for retrieving the coal dust carried up the flue. This dust is too coarse for mixing with the finished product and is therefore put through the pulverizer with the dried coal. In one plant this dust is used for firing the driers, being burned in suspension.

Fuel and Power Required for Drying.—Figures 116* and 117,* respectively, show the consumption of fuel and power for heating and rotating a certain type of machine when drying different fuels to a residual moisture content of 1 per cent.

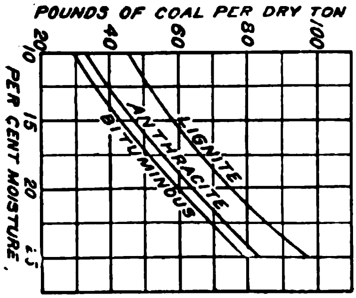

FIG. 116.—Coal required for drying various fuels. (*Reproduced from "Utilization of Waste and Undeveloped Fuels in Pulverized Form," by V. Z. Caracristi, Gen. Elec. Review, Sept.*, 1917.)

Temperature Control in Drying.—The coal should only be raised to a sufficient temperature to drive off the moisture without the distillation of volatile gases. A pyrometer should be installed to indicate to the operator the temperature to which the coal is

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* From "Utilization of Waste and Undeveloped Fuels in Pulverized Form," by V. Z. CARACRISTI, *Gen. Elec. Rev.*, September, **1917**, 698.

exposed. If the coal is ignited from overheating, a smouldering fire may be carried through a screen-type pulverizer and into the storage bins.

L. H. Bergman* makes the following interesting observations regarding the operation of the dryer, which he considers the most important unit in a coal milling plant. If this machine is capable of delivering a *dry* and *cool* coal, some fundamental requirements for the successful operation of a pulverized coal plant are fulfilled. The dryer should be fed uniformly, and be supplied with an even heat, which can only be obtained by firing it with pulverized coal. The burner should have a positive feed which can be set in accordance with the moisture content of the coal fed into the dryer.

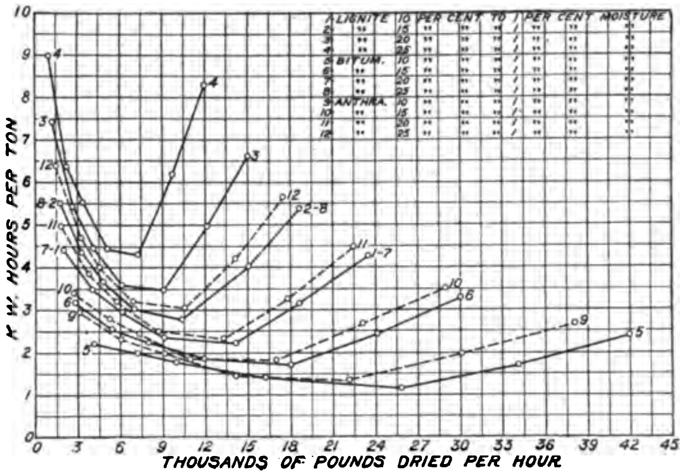

FIG. 117.—Power required for rotating the dryer (see Fig. 116).

A very important point is that the coal shall be discharged from the dryer at a low temperature, although this requirement can only be met by sacrificing the thermal efficiency of the dryer to some extent. The latter will operate most economically when the inlet temperature is high and the temperature of the outgoing gases is comparatively low. This necessitates a rather high temperature at the delivery end of the dryer and, consequently, the coal will be hotter than is desirable.

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[*] Vice-president, American Industrial Engineering Co., Chicago, Ill. (Private communication.) Formerly in charge of pulverized coal plant at the Midvale Steel & Ordnance Co.

Bergman states that for a comparatively long period he operated a dryer which discharged the coal, at a temperature of over 93°C. (200°F.), into an elevator which conveyed it to the dry-coal bin. The fan action of the elevator would also draw in some of the surrounding hot gases which, at this temperature, were saturated with water vapor and this would condense on the sides of the bin. This water ran down the sides of the bin and dripped from the bottom. As a result, a layer of mud collected in the bin and had to be cleaned out every 6 weeks, which necessitated a shutdown and a considerable expense. Another result was that the dried coal could not be stored in this bin for more than 24 hr. without spontaneous combustion.

During this time the coal had frequently to go right through the bin and the screen-type pulverizing mills, and on to the storage bins at the furnaces. Under these conditions, as a rule, spontaneous combustion developed within 48 hr. in the pulverized coal.

The operation of the dryer, therefore, was changed to allow the coal to be discharged at a temperature of about 38°C. (100°F.). Also, the bin was provided with a large vent pipe. The condensation in the bin was eliminated and the dried coal could be kept in storage for a sufficient length of time. Then, after pulverizing, this coal could be stored in the furnace bins, without spontaneous combustion or taking up any appreciable amount of moisture. In fact, when furnaces were started on coal which had been in storage for over 6 months, it could be handled and burned just as well as freshly pulverized coal.

In the latter case the coal was pulverized in air-separation mills, but coal pulverized in screen-type mills has been carried in storage in other plants, to the author's knowledge, for long periods without trouble from spontaneous combustion. Available evidence points to the conclusion that freshly mined raw coal gradually loses its tendency to ignite spontaneously, especially after rehandling, and that the same thing is true in the case of freshly pulverized coal. In other words, if it will ignite at all in storage, it will do so within a limited period, and this may be avoided by delivering it to the bin in a cool and dry state.

In the case of coals with a moisture content not exceeding 6 per cent, it has recently been found that dryers may be dispensed with.

Magnetic Separators.—These are necessary for removing "tramp iron" from the coal before pulverizing. They are installed either between the dryer and the dried coal storage bin, or ahead of the crusher. Figure 118 shows the pulley type of magnetic separator, which is placed on the drive end of the conveyor belt, non-magnetic material being thrown beyond the pulley, while magnetic material clings to the belt until it passes under the pulley. Figure 119 shows a fixed type of magnetic separator. These are sometimes placed above the belt to attract tramp iron. In other instances they are placed at the bottom of the chute.

FIG. 118.—Two types of magnetic separators. (*Reproduced by courtesy of Fuller-Lehigh Co.*)

PULVERIZING

Theory of Grinding.*—Economical grinding is merely making surface at the least expenditure for power and upkeep. The superficial area of a decimeter cube (using the metric system for convenience) is 6 sq. dm., or 600 sq. cm.

By shearing this cube into equal rectangular blocks, the surface is increased as follows:

Into 2 blocks, 33.3 per cent increase.
Into 4 blocks, 66.6 per cent increase.
Into 8 blocks, 100.0 per cent increase.

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* Condensed from bulletin published by F. L. Smidth & Co.

Continuing the division, the surface will be increased as follows:

Cubes		Corresponding Mesh	Increase in Surface Area, Times
Side	Number		
1.0 cm.	1,000	No. 2 or 3	10
1.0 mm.	1,000,000	No. 20	100
0.1 mm.	1,000,000,000	No. 180	1,000

Power in grinding is expended in destroying cohesion. The force of cohesion varies between the extremes of known breaking stresses. Cohesion in all materials to be ground includes a property known as grindability. Glass, though very hard, is easily grindable; graphite, though very soft, is difficult to grind.

General speaking, all grinding is accomplished by placing the materials to be ground between two surfaces and bringing the surfaces together under stress.

The whole surface upon which the grinding medium must act is one-half of the newly formed surface. In breaking a cube into two equal pieces, one unit of power is used, but two units of surface are created. The distribution of the power may be defined, approximately, in the case of the reduction of the decimeter cube, by considering the new surface created at each stage of the reduction. The original surface of 600 sq. cm. is increased to 6,000 by the first reduction, of which 5,400 sq. cm. are new surface. The power has acted on one-half of this, or 2,700 sq. cm. Similarly, it will act on 27,000 sq. cm. at the second reduction and on 270,000 at the third, making a total of 299,700 sq. cm.

It is obvious from this that the efficient application of the power is divided into 0.9 per cent for crushing, 9 per cent for granulation, and 90 per cent for pulverization. That is to say, the energy is consumed in proportion to the surface created; the power required to crush a 1 mm. cube is small, but the number of pieces using that power is great. The power varies with the fineness required and with the grindability of the material.

The grindability of materials of practically the same chemical structure will vary more than 100 per cent. Therefore, the grindability of a material must be determined by actual tests before the output of any grinding machine can be determined.

As mentioned on page 683, a 1-inch cube of coal, when reduced to the proper degree of fineness for burning in suspension, has a superficial area of from 20 to 25 sq. ft. Thus the original surface is multiplied between 480 and 600 times.

The foregoing theory of grinding is known as Rittinger's Theory and is expressed mathematically as follows:*

Assume a homogeneous 1-in. cube which requires A ft.-lb. of work to divide it on a plane parallel to one of its faces. To divide it into—

8 $\frac{1}{2}$-in. cubes requires three planes and work is $3A$ ft.-lb.;
27 $\frac{1}{3}$-in. cubes requires six planes and work is $6A$ ft.-lb.;
64 $\frac{1}{4}$-in. cubes requires nine planes and work is $9A$ ft.-lb.;
125 $\frac{1}{5}$-in. cubes requires 12 planes and work is $12A$ ft.-lb.;
$N^3 \frac{1}{n}$ in. cubes requires $3(N - 1)A$ ft.-lb.; and
$M^3 \frac{1}{n}$ in. cubes requires $3(M - 1)A$ ft.-lb.

The ratio of the work required in two different cases will be as $N-1$, $M-1$, where N and M are the reciprocals of the diameters crushed to. In most cases the values of M and N are large enough so that the 1 can be neglected and the law then stands that the work is very nearly proportional to the reciprocals of the diameters crushed to. Thus to crush a 1-in. cube into $\frac{1}{20}$-in. cubes will require about five times as much work as to crush it into $\frac{1}{4}$-in. cubes.

Methods of Grinding.—The various types of pulverizing machinery utilize several distinct principles in grinding solid materials, viz.:

1. Shearing.
2. Attrition, by abrasion under pressure.
3. Crushing by pressure.
4. Crushing by impact on anvil.
5. Shattering by impact in space.

Several of these principles may be used simultaneously in the same machine. In the old fashined Buhr millstones corn and grain were ground, partly by the shearing action of the ridges on the surfaces of the stones and partly by abrasion under pressure between the upper and lower stones.

A common modern method of milling grain consists in crushing it between a pair of smooth rolls. This was one of the earlier methods used for pulverizing coal. It was first crushed to a granular size, and the capacity of the rolls was greatly limited by the narrow gap required for fine grinding.

A modern application of this principle is used in the "ring-roll mills," where the material is ground between a large ring and one or more internal rolls which roll or slide in contact with the inner

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* From "Ore Dressing," by A. H. Richards, 1, 304.

surface. Sometimes the ring rotates and the rolls are pressed against it by springs. In the majority of these mills the rolls rotate and press against the ring by centrifugal force. In either case they are free to ride over coarser material.

Slowly moving rolls crush by pressure, while the more rapidly moving rollers in the ring-roll mills crush the larger pieces of material by impact and the finer material by pressure. The granular material is also reduced by the mutual attrition of the particles under the pressure of the rolls, or by the direct attrition of sliding rolls. The best example of crushing by impact occurs in the ball mill and tube mill under the bombardment of the balls or slugs. Shattering by a blow in space is the action utilized in most of the types of high-speed pulverizers, such as hammer mills and beaters.

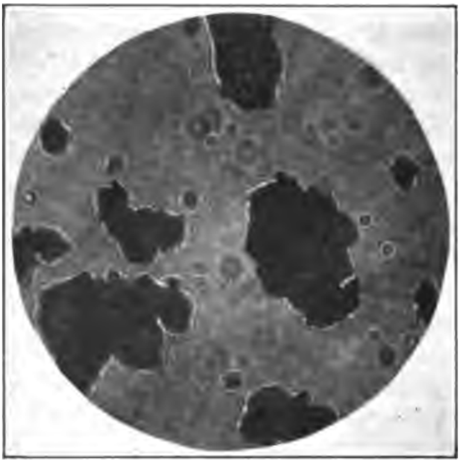

FIG. 119.—Pulverized coal, magnified 560 diameters. (*Published through the courtesy of the Pulverized Fuel Equipment Corporation.*)

The difference between crushing by pressure and by impact is largely one of degree, the effect being magnified in the latter case by the inertia of a moving body. The difference between abrasion and shearing is also one of degree, for the reason that abrasion is due to the shearing action of the small elevations on a rough surface. Scientifically considered, crushing takes place by shearing and the latter action is the fundamental one.

Many of the commercial types of pulverizing machinery were developed for grinding cement materials, which include relatively hard substances, like limestone and cement clinker. Coal, being a softer material, is easier to pulverize. It is, however, a stratified mineral and its structure is frequently such that many of the granular particles take the form of flat flakes which are somewhat difficult to pulverize when mixed with fine material. Many of the minute particles also take the form of flakes, as shown by the photomicrograph, in Fig. 119.

Carbonized Fuels.—Carbonized fuels are harder and more difficult to pulverize than bituminous coal. It will require less weight of a bulky fuel like coke to fill a pulverizer, although the material may be fed to the mill at about the same rate by volume measurement. Tests made in pulverizing 72-hr. beehive coke, or by-product coke, in a Fuller mill show that the power requirements are approximately 45 per cent greater than when pulverizing bituminous coal from the Pittsburgh district. In the latter case about 12 hp.-hr. are required per ton of coal, as against 17.5 hp.-hr. per ton of coke. Tests made in grinding a semi-coke, with a volatile content in the neighborhood of 9 per cent, showed it to require more power than coal.

To get a rough idea of the relative physical characteristics of different fuels, the author has ground several materials with a mortar and pestle, including bituminous coal, semi-coke with about 15 per cent volatile, semi-coke with about 9 per cent volatile, gas retort breeze and by-product coke. The difficulty of pulverizing increased approximately in the order given. The semi-coke samples which happened to be available were made by different processes: the one with 15 per cent volatile was subjected to pressure during distillation, which diminished the cell space, while the lower volatile sample was of open cellular structure. The denser sample with the higher volatile content, was nevertheless, honeycombed with air cells and was easily crushed, and required only a little more effort to pulverize than bituminous coal. The more cellular sample, with lower volatile content, crushed very easily, but the fragments of the cell walls were extremely tough and hard. Anthracite, also, is difficult to pulverize by hand.

It would appear, therefore, as if the less carbonized semi-coke were preferable for economical pulverizing, as well as for burning in suspension in pulverized form. This is what one would naturally expect, but the number of samples available for pulverizing was not sufficient to give positive confirmation. On page 467 it was stated that the more valuable oils are recovered by the time the coal is reduced by distillation to a volatile content of about 15 per cent. Further distillation at low temperature yields mainly fixed gas, which might better be left in the coke to make it ignite more readily when burned in suspension.

When carbonized at temperatures above its fusion point, bituminous coal loses its original crystalline structure and breaks less frequently into thin flat particles. However, when distilled until the volatile content is reduced to about 10 per cent, or less, the cell walls are carbonized to a smooth and hard substance which sometimes breaks into flat particles when pulverized, even though their appearance is different from the flat particles of raw coal. The degree of carbonization can be controlled by the time of passage through the retort, even if the temperature in the retort is held at the same point.

Fineness of Grinding.—A screen test, to be of value, must be made with an accurate square mesh testing sieve. The screens are mounted in seamless brass rims and are tightly stretched. Bottom pans are used to catch the fine material for weighing, and the hand method of sieving gives the best results. The dimensions of the openings in standard screens are given in Table LXXXII.

TABLE LXXXII.—TESTING SCREENS OF WIRE MESH CLOTH

MESH OPENINGS PER LINEAR INCH	WIRE DIAMETER, INCHES	OPENING WIDTH, INCHES	OPENINGS PER SQUARE INCH
100	0.0045	0.0055	10,000
200	0.0021	0.0029	40,000
300	0.0016	0.0017	90,000

For ordinary purposes, a fineness of 95 per cent through 100-mesh, and 85 per cent through 200-mesh, is considered the standard to be lived up to. This was established, originally, in the cement industry and is also used in pulverizing coal for boilers and for most types of metallurgical furnaces. However, to allow for wear in the pulverizing elements of the mills, a fineness of 90 per cent through 100-mesh and 75 per cent through 200-mesh may be considered satisfactory as a lower limit, and the product should be relatively free from particles which will not pass through an 80-mesh screen;* and all should pass through a 50-mesh screen.†

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* "Pulverized Coal for Locomotives," by V. Z. CARACRISTI, *Gen. Elec. Rev.*, November, **1917**.

† H. G. BARNHURST, *Mech. Eng.*, September, **1919**, **756**.

Finer grinding is necessary for certain work, as already mentioned in connection with open-hearth steel furnaces. For firing locomotive boilers a fine product is also desirable because of the limited dimensions of the firebox and the rapidity with which the particles pass through the combustion zone. When burning low-volatile fuels in suspension, the lack of volatile matter can be compensated for, to some extent, by fine grinding. The upper limits for fineness, mentioned in Table LXXII, were taken from locomotive practice; probably 99 per cent through 100-mesh and 97 per cent through 200-mesh is about as fine as it will pay to pulverize fuel for use on a large scale.

Commenting upon the tests recently made at the Lakeside station of the Milwaukee Electric Railway and Light Co. (page 735), W. J. Risley, Jr., makes the following interesting observations:* It has been shown that the time-honored figure of 80 to 85 per cent through a 200-mesh screen, necessary for good conbustion, is too high, and that it is much more important that the combustion chamber be properly designed than that the fineness should be so high. The fineness necessary depends largely on the specific gravity of the fuel. When the fuel is specifically lighter, larger particles can be carried along in the air current; and when the specific gravity is higher, the particles must be smaller.

The following percentages through a 200-mesh screen were ound advisable for different ranks of fuel:

Peat	50–60 per cent
Lignite	65–70 per cent
Bituminous coal	73–80 per cent
Anthracite coal	80–86 per cent

Control of Fineness.—The fineness of the product is controlled by three general methods:

1. Rate of feed of raw material.
2. Screening the product.
3. Air separation.

1. *Feed control* is exemplified in the old fashioned Buhr millstones and in a modern prototype, the Sturtevant rock emery mill, which is used for grinding coke, retort carbon and other

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* *Power*, August 23, **1921,** 301.

materials for manufacturing purposes. The slower the material is fed, the longer it remains in the mill and the finer the product. This is also the case in the ball mill and tube mill, although external screens are sometimes used for granular material.

2. *Internal screens*, in the form of steel-bar gratings, are used in hammer mills for screening the granular product and are set close to the rotating elements. Internal screens are also used in several types of ring-roll mills which are employed for grinding coal, including the Kent, Griffin and Fuller mills. The Kent and Griffin mills are in use in some of the older installations.

The Fuller mill is the chief type of modern coal pulverizer which separates the finished product by means of a screen. This mill is built for use with either screen or air separation, but the manufacturers are strong advocates of screen separation for the reason that it keeps the material in the mill for a sufficient time to permit of the reduction of many of the particles to an impalpable powder, fine enough to allow portions of it to pass through screens of 300- and even 600-mesh. This extremely fine material, it is claimed, facilitates rapid and complete combustion of the coal.

3. *Air separation* is used in most of the other types of coal pulverizers. A current of air is drawn through the pulverizing zone and picks up the fine particles as soon as they have been reduced sufficiently in size. This keeps the pulverizing zone free of fine material which would otherwise cushion the blows of the grinding elements. Some coarser material is carried away by the air and is separated outside the mill by reducing the velocity of the air in an expansion chamber. This allows the larger particles to drop out and return to the mill by gravity. Expansion chambers are shown in Fig. 114, on the McCool pulverizer, in Fig. 170, on the Bonnot mill, and in Figs. 123 and 124, on the Raymond mill, being of a different shape in each mill.

The internal construction of the Raymond separator is shown in Fig. 123. It consists of two galvanized-steel cones mounted concentrically on the top of the mill casing. The air is introduced through a volute casing which surrounds the pulverizing ring and delivers the air, just below the latter, through vanes which give it a spiral motion. The air rises by the ring and rolls and carries the coal particles up through the annular space between the two cones of the separator. The circulating fan exhausts the air from the inner cone; the air from the outer cone, being drawn through adjustable dampers at the top, expands into the slight vacuum, loses its velocity and drops the coarser particles back into the mill. The fineness of the product may be controlled by varying the velocity of the air.

The air, carrying the finished product in suspension, passes through the fan and is generally used as a conveying medium for elevating the coal to a convenient point for dropping it into a bin, from which it may be distributed by other means (Fig. 132). In order to separate the coal, the air is discharged tangentially into the top of a conical cyclone collector which is located above the bin. The resulting rotary motion effects part of the separation centrifugally, and is aided in this by the expansion of the air as it moves toward the center with loss of velocity.

The air is circulated in a closed circuit in order to avoid the loss of fine dust. In the part of the system where the air is laden with coal, it is under a slight vacuum and this prevents outward leakage. Any air leakage will be inward and will be vented, beyond the cyclone collector, through a small branch pipe which is usually fitted with a small auxiliary cyclone collector for retrieving fine dust.

In some installations of Raymond mills the air discharged from the auxiliary cyclone collector is passed through a tubular cloth filter which recovers the residual fine dust (see page 587). This makes it possible to circulate a certain proportion of fresh air through the circuit, which tends to cool the mills and to remove the moisture released from the coal during grinding.

Some advantages claimed for air separation are:

(*A*) Freedom from screen troubles, such as puncturing by foreign material in mill, and crystallization, which normally limits the life of screens.

(*B*) The material may contain a larger percentage of moisture than when screens or feed control are used, and it is well aerated and cooled after pulverizing.

(*C*) By promptly removing fine material from the mill, the pulverizing rolls are left free to act exclusively on coarse material and no energy is expended in reducing fine dust to a smaller size than absolutely necessary. The product is, therefore, of a more uniform size than with screen or feed control.

(*D*) Separate conveyors and elevators are not required for delivering material to the bin. (*C*) and (*D*) together may offset the power required to drive the fan.

Types of Pulverizers.—The commercial machines used for crushing and pulverizing coal may be classified broadly, according to the speed of rotation, as shown in Table LXXXIII.

TABLE LXXXIII.—MACHINES USED FOR CRUSHING AND PULVERIZING COAL AND COAL PRODUCTS, CLASSIFIED BY SPEED

Type	Feed, maximum size	Product, maximum size	Fineness control
(*A*) 600–2,300 r.p.m.; direct motor drive:			
Hammer mills	Run of mine or crushed	½ in. to 20-mesh	Grid
Beaters	Crushed to 2 in. or less	Pulverized	Air
Paddle mill	Crushed	Pulverized	Air
(*B*) 300 to 1,000 r.p.m.; belt drive:			
Disc mill	½ in.	Pulverized	Air
Rock emery mill	Granular	Pulverized	Feed
(*C*) 100 to 400 r.p.m.; belt or gear drive:			
Ring-roll mills	¼ to 1½ in.	Pulverized	Air or screen
Rotary fine crushers	....	½ to ⅛ in.	Spacing
(*D*) 30 to 100 r.p.m.; gear drive:			
Single-roll crushers	Run of mine	¾ to 4 in.	Spacing
Double-roll crushers	Crushed	⅜ in. and upward	Spacing
(*E*) 20 to 35 r.p.m.; gear drive:			
Ball mill	2 to 3 in.	15- to 20-mesh	Feed
Tube mill	15- to 20-mesh	Pulverized	Feed
Combination mill	1½ to 3 in.	Pulverized	Feed

(A) **High-speed mills** include hammer mills for crushing and beaters for fine grinding. The former discharge their product through a grid in the casing, while the latter have a closed casing and operate with air separation. Several types of beaters operate on closed circuit grinding, while the multi-stage paddle mill operates on open circuit (see page 582). Much of the grinding in beaters is effected by blows upon the material while it is in space, or by crushing between the hammers and the casing. The prevalence of the former action sometimes renders the preliminary drying of the material less necessary, or makes it possible to pulverize gummy materials. Coal, however, can usually be pulverized more economically when dry.

The Raymond impact pulverizer is a small machine of the beater type and is sometimes used for pulverizing petroleum coke and retort carbon for electrical purposes.

The Stroud mill is used for pulverizing coal, the largest size having a capacity of from 4 to 5 tons per hour. Most of the work of grinding is done by mutual attrition between the coal particles, which, it is claimed, reduces the wear to a minimum. This machine operates at 1,900 r.p.m. and consumes from 8 to 10 hp. per ton of coal pulverized.

The American Pulverizer.—This machine has formerly been used as a hammer mill for crushing coal, coke, brick and rock, the crushed material being discharged through a grid in the casing. A new model has recently been developed with a closed casing and designed especially for pulverizing coal. It is operated as a beater in closed circuit with a Clark air separator (page 602) and at a relatively low speed, 600 r.p.m. The rotating element has four radial arms which are connected by axial rods at the outer ends, 2 in. in diameter.

The pulverizing elements are manganese steel rings which are loosely mounted on the rods, the latter passing through the holes in the rings. These holes are 6 in. in diameter, so that the rings are free to fly out by centrifugal force until their outer edges swing just clear of the stationary casing, the radial clearance being 3⁄16 in. The rings are thus free to swing when overriding lumps of coal and to act either as hammers or rolls.

The casing is lined with manganese steel plates and much of the grinding action takes place by mutual attrition between particles of coal as they are crushed between the rings and lining. The rings pass any given point 10 times per second. They weigh 27 lb. and the centrifugal force of each ring is 3,600 lb., while its kinetic energy is 2,000 ft.-lb., so that the resultant blows are sufficiently heavy for effective grinding.

The relatively low speed of this machine should considerably reduce the wear on the casing and runner, which is one of the limitations of some types of high-speed mills. It operates with only a slight humming noise, owing to the fact that the pulverizing elements do not run in actual contact with the casing.

The capacity of a No. 48 mill ranges from 3.5 to 4.5 tons of bituminous coal per hour, or from 2.5 to 3.5 tons of anthracite, 90 per cent. of the product passing through 200-mesh in each case. The power required is 75 hp., or less.

The Aero pulverizer is of the multi-stage paddle type and is illustrated in Figs. 120 and 121. This machine operates on open circuit and is always installed on the "unit system," no separator being used. Figure 105 shows a typical installation in connection with a cement kiln, no dryer being used in many cases, although some users have found it desirable to dry the coal. The paddles are of manganese steel and are carried on discs which are mounted on the shaft. In the first stage, pulverizing and crushing take place largely by impact; but as the material is successively reduced in the following stages, the smaller particles are carried forward by the air current and are fanned to the periphery where the entire mass of coal rotates in contact with the lining of the casing. Pulverizing action takes place

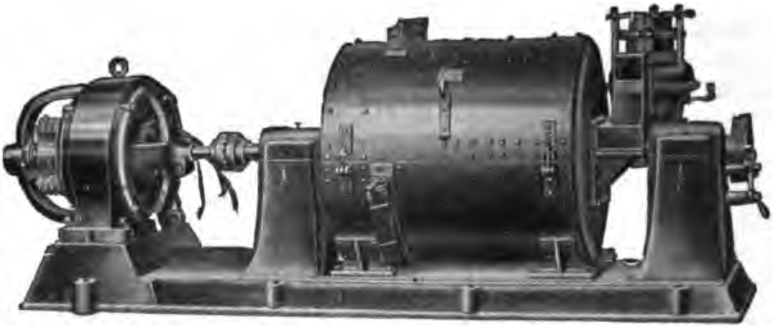

FIG. 120.—Aero pulverizer with direct-motor drive.

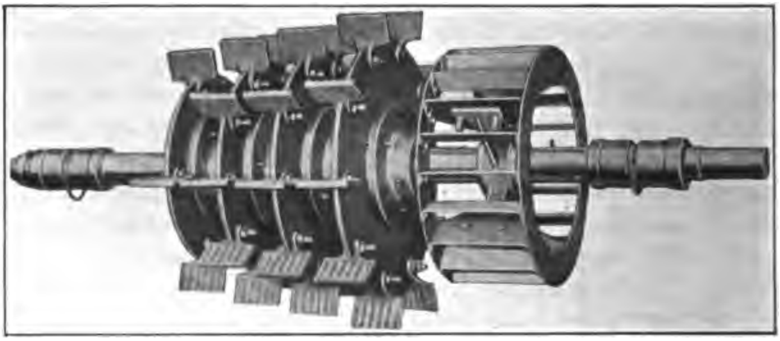

FIG. 121.—Rotor for type "E" Aero pulverizer.

largely by the mutual attrition of the particles of coal. This machine was one of the pioneers in the art of using powdered coal and has been successfully used for firing rotary kilns and dryers. It is applicable for grinding the softer materials but not for coke. Air is not used for separating the coarse material outside of the machine, reliance being placed on the number of stages in series.

(B) **Disc mills** include the Sturtevant rock emery mill, used for coke and retort carbon, and iron disc mills used for ore and coal grinding in small units.

The McCool pulverizer is of the latter type and is illustrated in Fig. 114, which shows the largest size. This machine runs at 600 r.p.m. and has a capacity of from 600 to 1,500 lb. of coal per hour, 11 hp. being required. This machine is used in a few small boiler plants in western mining districts. The smallest size has a capacity of from 15 to 40 lb. of coal per hour and requires 1 hp. It is mounted on the sides of small assay furnaces for firing them on the "unit system," as mentioned in connection with metallurgical furnaces. No drier is used.

(C) **Ring-roll mills** include the types of mills most frequently used for pulverizing coal. Many types of ring-roll mills are used in the cement industry, both for preliminary grinding and as finishing mills, in either the wet or dry process. A number of types are used for pulverizing coal, but only four need be considered, as these are the ones which are suitable for the fine milling of coal. These may be subdivided, according to the construction of the internal parts, into two classes:

Non-lubricated type:
  Fuller-Lehigh mill;
  Bonnot mill.

Huntington type:
  Raymond mill;
  Kennedy-Van Saun mill.

In all of these the pulverizing elements consist of a stationary ring within which slide or roll either spherical balls or cylindrical rolls which are driven by means of a spider, mounted on the shaft. In the non-lubricated type this spider pushes the balls or rolls and is not rigidly connected to them. This avoids the necessity for periodic shut downs for lubrication and renders continuous operation possible. The Huntington type mills are designed along similar lines to a mill of that name which is used for the preliminary grinding of cement materials and for coal. The two mentioned, however, are especially designed for fine grinding with the aid of air separation. In these mills there is a positive mechanical connection between the spider and the rolls which contains a lubricated journal. This is lubricated with grease at certain intervals and the wear of the parts is thus reduced to minimum.

The rollers are hung from the arms of the spider and are pivoted to allow freedom for radial movement in riding over the coal.

The Fuller-Lehigh mill.—The internal construction of this mill is shown in Figs. 165 and 166. It might be described as a "ball and race mill," and the grinding ring is a chilled iron casting of concave vertical section. The forged steel balls are propelled by the four arms of the pusher which act as brakes and retard their rotation, to some extent, with the result that they are made to slide a little while rolling around the grinding ring, but it may be broadly classed as a ring-roll mill. This mill, consequently, is claimed to give the closest imitation to a mortar and pestle action, which conduces to fine grinding and the reduction of the flat coal particles by attrition.

As soon as the material is reduced to the desired fineness, it is lifted out of the pulverizing zone by the inclined plows mounted on the rotating element just above the balls. These discharge the coal into the path of the upper radial blades, which fan it against the internal face of the cylindrical screen by centrifugal action. At the same time, the lower radial discharge fan, located just below the grinding ring, creates a suction on the external face of the screen through the narrow annular space between the inner frame and the outer casing of the mill. Thus a light current of air is drawn through the screen, which keeps it clear and carries with it the finished product. The coal which is still too coarse to pass the screen falls back into the pulverizing zone for further grinding.

A double screen is used, the finer one being on the outside, where it is protected by a coarse inner grid which stops the coarser lumps. In this mill the crushing force is applied to a limited amount of material, and the reduction is effected with a minimum expenditure of power. The sliding action of the balls produces a large percentage of impalpable power which, it is claimed, aids rapid combustion.

Figure 122 shows an installation of Fuller mills pulverizing cement rock and illustrates the preferred method of belt drive from a vertical motor. The largest unit has a grinding ring 56 in. in diameter and a capacity of more then 8 tons of coal per hour, and operates at 130 r.p.m. This mill is built in four sizes with grinding rings of from 24 to 56 in. in diameter. The capacities range from one-half ton to something over 8 tons per hour, and the speeds from 300 to 130 r.p.m.

FIG. 122.—Installation of Fuller mills belted to vertical motors.

This mill is used for grinding harder materials than coal ranging from cement rock to emery. Red-ash anthracite from Lykens, Pa., has been satisfactorily pulverized in the same mill as is used for grinding bituminous coal. When grinding the harder white ash anthracite of lower volatile content, mined in most of the anthracite districts, the mill should be fitted with parts made of special materials capable of resisting the abrasion.

When grinding various grades of bituminous coal, the capacity of the mill will vary possibly 20 per cent above or below the average, according to the ash content and hardness of the coal. When grinding anthracite the output will average about 75 per cent of the average capacity on bituminous coal, ranging from 85 to 65 per cent. with different grades of anthracite.

The Bonnot mill is shown in Fig. 170. It differs from the other three ring-roll mills described in having a horizontal shaft. The grinding ring is made of a special grade of tough steel and is rolled to give it maximum density. The inner surface is concave, which assists in holding material in the path of the rolls. The latter are made of a special mixture of metal with a hard wearing surface. A shaft is inserted in the center of each roll and the short protruding ends form gudgeons which lie in pockets provided in the driver casting. They serve to guide the roll and keep it in line with the center of the grinding ring, the actual propulsion of the rolls being effected by the arms of the driver which bear on the back side of the roll, as in the Fuller mill.

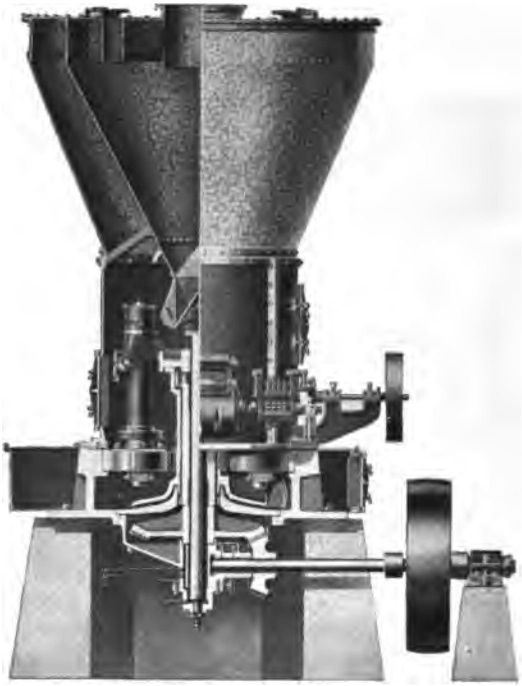

FIG. 123.—Half-sectional view of high-side Raymond mill.

This mill is built with grinding rings of 18 and 36 in. diameter, the two units having approximate capacities of 1¼ and 5 tons of coal per hour, and operating speeds of 400 and 225 r.p.m. This mill is equipped for either screen or air separation, according to the material being ground, air being used when pulverizing coal

The Raymond roller mill is shown in Figs. 123 and 124, while the rotating element, including the spider and plows, is shown in Fig. 125 and the roller and its journal in Fig. 126. The grinding ring, commonly called the bull ring, is made of a special grade of high-carbon steel and differs from the last two mills described in having a cylindrical inner surface. The manganese steel plows throw the material into the path of the rollers, which are suspended from the spider, as shown in Fig. 123. The rollers are made of cast iron with deeply chilled faces and are mounted on the lower end of a shaft which rotates in a long journal, lubricated with grease. The journal and roller are suspended by a short horizontal shaft of hardened steel, which is rigidly clamped in the spider at both ends and serves as a pivot to allow the roller to rock.

FIG. 124.—Raymond mill with cyclone separator.

The mill is fitted with single- or double-shell separators, according to the fineness of product required. Mills thus fitted are known, respectively, as "low-side" and "high-side" mills. The latter type is recommended for fine grinding and is the one shown in Figs. 123 and 124. Both types are used for grinding coal.

This mill is built in four sizes, having from 2 to 5 rollers, and with capacities for grinding from 2 to 5 tons of coal per hour to a fineness of 95 per cent through 100-mesh. A product with a fineness corresponding to 99 per cent through 100-mesh, and 92 per cent through 200-mesh, may be obtained by operating the high-side mills at a lower capacity, ranging from 1.2 to 3 tons per hour, for the various sizes of unit. Material may be fed containing lumps of from ¼ to 1½ in. in maximum size. The five-roller mill and exhauster are driven by a 85 hp. motor. The actual power consumption is given in one of the tables on the tests at the Milwaukee Electric Railway & Light Co.* in the latter part of this chapter.

FIG. 125.—Rotary element of Raymond mill with spider and plows.

FIG. 126.—Roller and journal, Raymond mill.

The Kennedy-Van Saun mill is a new design of ring-roll mill of the Huntington type. It differs from the Raymond mill as regards a few mechanical details, the air current being

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* The authors are indebted to W. A Koren for information.

introduced into the center of the mill, at the bottom, instead of from the periphery. This mill is built with a ring die 54 in. in diameter and with from two to five rollers of about 17 in. diameter. It is recommended that the material should not be fed in sizes greater than ½ or ¾ in. lumps.

The general principle of operation, in all the ring-roll pulverizers, is such that the most efficient operation is secured when the raw material contains lumps of from ¼ to 1¼ in. in maximum size, according to the size and characteristics of the individual machines. The presence of the coarser material keeps the rolls in constant vibration as they strike and ride over the lumps, so that pulverization takes place by impact as well as by crushing and attrition. If fine material only be fed to the mill, more of the reduction must take place by crushing and more power will be required per ton of output.

The mills of the ring-roll type are generally preferred for pulverizing bituminous coal, owing to their adaptability for fine grinding with a minimum power consumption, as well as for the reason that they can take a relatively coarse material and reduce it to a finished product in one operation. These mills are also used for pulverizing anthracite culm and coke breeze, the power requirements being considerably greater than for bituminous coal for the following reasons:

1. Hardness of the materials.
2. Fineness of material fed to mill.
3. Finer grinding required to secure ignition, owing to low volatile content.

As stated on page 585, the power requirements for pulverizing bituminous coal in a Fuller mill are about 12 hp.-hr. per ton, according to the manufacturers' tests. The equivalent electrical input is approximately 10 kw.-hr. per ton. The power requirements for pulverizing anthracite, according to a test made at the experimental boiler plant of the Susquehanna Collieries Co., at Lykens, Pa., was 22.5 kw.-hr. per ton. The size of the material fed to the mill is not stated, *i.e.*, whether buckwheat coal or silt. The condition of the two pulverizers is not stated, *i.e.*, whether the balls were new or worn. These factors, of course, influence the power requirements, but from these and other data it is evident that at least twice as much power is required for pulverizing anthracite culm as for bituminous coal.

(D) **Ball and tube mills** are sometimes used for pulverizing coal and have possibilities of interest in connection with anthracite slush and semi-coke. They are used very extensively for granulating and pulverizing ore and cement materials and are simple and rugged machines which operate at low speed, require very little attention and are well adapted for grinding hard materials. The short ball mill is used for preliminary granulating and is charged wth large steel balls. The tube mill is a longer cylinder, charged with smaller grinding elements. They are cylindrical steel drums with either flat or conical ends and are essentially large tumbling barrels. Originally, Danish flint pebbles were often used as the active pulverizing elements and the mills were lined with silex blocks.

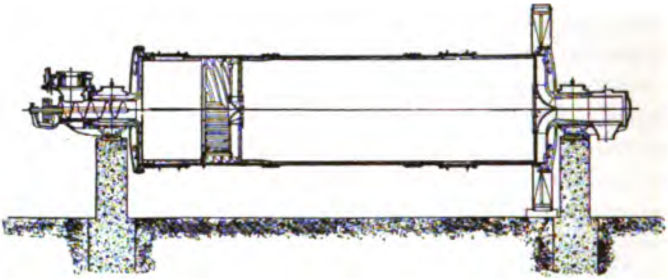
Fig. 127.—Longitudinal section of Allis-Chalmers Compeb mill.

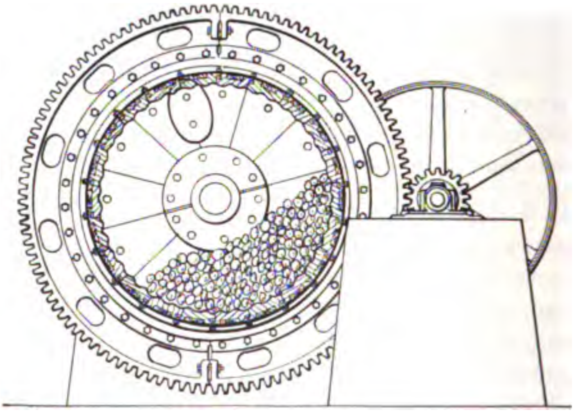
Fig. 128.—Cross-section of tube mill.

The pebbles, however, have been gradually replaced by metal balls or slugs and the mills are usually lined with chilled iron plates. Iron and steel balls or slugs have been found to be more effective than pebbles for grinding most materials, owing to their greater weight, and the capacity of the mills has been considerably increased by their adoption. Sometimes long steel rods are employed, but the usual practice is to use balls or short cylindrical slugs. In one plant steel boiler punchings are used for grinding coal, but the longest life is obtained when the elements are cast from special iron alloys.

A cross-section of a ball or tube mill is shown in Fig. 128. The charge usually occupies from 0.3 to 0.4 of the mill volume, the material being pulverized occupying the voids between the balls.

The efficient speeds for various conditions are given in Table LXXXIV.

Table LXXXIV.—Tube Mill Speeds[*]

Inside diameter of mill, feet	Critical speed, r.p.m.	Most efficient speed for cascading, r.p.m.	
		0.3	0.4 (volume of mill occupied by charge)
4	38.3	30.9	31.7
6	31.3	25.2	25.9
8	27.1	21.9	22.4

When starting a mill, the charge must first be lifted until the balls at the top commence to tumble down over the charge below and, if the mill be revolved at speeds which are sufficiently low, the centrifugal force will not be great enough to overcome the effect of gravity at the top of the charge and only a tumbling action will occur. This action is not confined to the material on the surface, but a general slipping and sliding action occurs throughout the charge, the upper layers sliding at a more rapid rate than the center of the mass. All parts of the mass are sliding at different velocities and the material is reduced either by attrition or by crushing action under the weight of the superincumbent charge.

The critical speed of the mill is reached when the centrifugal force becomes great enough to hold the outer balls in contact with the shell lining in opposition to gravity. The outer layer

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[*] "Fine Crushing in Ball Mills," by E. W. Davis, *Am. Inst. Min. Eng. Bull.*, Feb. **1919**, 111 to 156.

of the charge will then become ineffective and will reduce the effective diameter of the mill. With a bulky charge there will still be agitation in the inner zones and some materials are ground at speeds above the critical speed.

At speeds intermediate between the tumbling and critical speeds, the balls, as they reach their maximum elevation, are projected horizontally into space and cascade in a parabolic trajectory to the bottom of the mill, along with the material being ground, as indicated in Figs. 129, *A* and *B*. Here they strike the part of the charge which has fallen ahead of them, or on the lining of the mill, and reduce the material by impact. Before the charge can reassume a circular motion with the mill, however, the direction of motion of the balls and particles must be changed through a right angle, and this is accompanied by considerable agitation, which extends back into the central zone where a tumbling action is maintained by which some material is reduced by attrition. This material in the center tumbles down into the path of the cascading charge and overshoots onto the lining at the bottom, thus forming a layer which protects the lining from the direct impact of most of the balls.

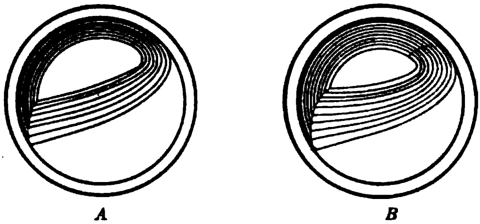

FIG. 129.—Theoretical curves indicating the path of the charge in ball and tube mills. In *A* the charge occupies 0.3 of the mill volume. In *B* the charge occupies 0.4 of the mill volume.

The terrific bombardment of the cascading balls subjects the material at the bottom of the mill to a crushing and grinding action throughout its entire mass, and the material is reduced, not only by direct impact, but by crushing and attrition by mutual action between the balls and the lumps of material.

Ball and tube mills are operated either at tumbling or cascading speeds, depending upon whether the particular material can be ground to better advantage by attrition or by impact. Soft or fine materials can sometimes be more economically ground by attrition, while hard, brittle, abrasive and coarse materials can be more economically ground by impact since the balls are not then subjected to as much wear by abrasion.

Among the mill maufacture's there are several schools of grinding: One advocates the grinding of coal and similar materials by attrition at tumbling speeds in short mills with conical ends, while another school advocates the long cylindrical or tube mill operated at cascading speed and grinding by impact. The latter method is used in the wet-milling of ores.

Open-circuit Grinding.—Mills are operated either on open circuit or closed circuit. In open-circuit grinding the material is passed through the mill only once and multi-stage reduction is generally necessary if coarse material is to be reduced to 200-mesh size (see page 573). In some cement plants coal, after being crushed with rolls, is granulated in a ball mill to pass a screen of from 14- to 16-mesh. Then it is fed into the tube mill by a screw located in the hollow trunnion and gradually migrates toward the discharge trunnion at the opposite end by displacement. Within certain limits the fineness of the product may be controlled by the rate of feed, and the fine material works ahead of the coarser to some extent in migrating toward the discharge end. The fineness is also controlled by the size of the feed. When grinding coal to standard fineness, if the feed is too coarse, the final product may contain material which is too coarse to remain in suspension in the furnace. On the other hand, much of the finished material remains in the mill until it is reduced to particles which might pass screens of 400 to 1,000 meshes per inch (if it were possible to make such screens). This unnecessarily fine grinding consumes power, and the presence of fine material protects the coarser material from attrition and tends to limit the output of the mill. Fine bituminous coal has more of a tendency to choke the mill than rock materials have because:

1. Although softer, the grindability somewhat resembles graphite and it has a lubricating action which prevents reduction by attrition.

2. Many varieties of bituminous coal tend to become compacted into small plates or flakes when in a finely divided state, if slightly damp.

Sometimes granulating and pulverizing stages are combined in one machine called a combination mill. This consists of a single cylinder with a division head between the compartments containing larger and smaller grinding elements. This eliminates the necessity for external screens between the last two stages. In the older installations, these screens often required an extra elevator and storage bin. They were made necessary by the fact that a finely granulated product had to be fed to the tube mills to secure satisfactory operation.

The granulating stage is usually charged with steel balls of sufficient size to break the largest lump of coal which will ordinarily be fed to the mill. The pulverizing stage is charged with smaller balls, which are more efficient for fine grinding. The size of the grinding elements is also determined by the diameter of the mill, a small cylinder requiring heavier balls to strike the required blow than a cylinder of larger diameter.

Closed-circuit Grinding.—Ball mills for granulating are often operated on closed circuit, the discharge from the mill being classified by screens external to the mill, the oversize product being returned to the mill for regrinding. Material may be passed through the mill five or six times before being reduced to finished size. This is a more economical method of grinding since the fine material is removed from the mill soon after being reduced to finished size. It is also a more positive method for obtaining a uniform product. External screens of the vibrating type are being tried experimentally.

Ball and tube mills are very extensively used in connection with the wet milling of ores and moist cement materials. Water is circulated through the mill and acts as a carrying agent for removing the finished material as soon as it is reduced to the desired degree of fineness. In wet grinding the mill is often operated in closed circuit with a hydraulic classifier, which separates the oversize in order that it may be returned to the mill for regrinding. Wet grinding is used for preparing ores for concentration by flotation or for cyaniding, as well as for hydraulic or magnetic concentration.

Wet-milling processes have not, heretofore, been applicable to coal, owing to the impracticability of drying coal after pulverizing on a large scale. The development of the Trent processes for cleaning coal (page 630) and for making water gas (page 374) will provide important fields for the wet grinding of coal.

Similar economies should be effected through the use of air separation in connection with dry milling in tube mills and conical ball mills. The air sweeping of the mill can be effected on open or closed circuit. In the former case, fresh air is drawn into the mill through the feed trunnion, is exhausted through the discharge trunnion and drawn through a centrifugal type of air separator (or a vibrating screen), where the oversize material is dropped out and returned to the feed end of the mill. The air is then drawn through a tubular cloth filter which is frequently shaken to remove the finished material. When the air reaches the suction fan, it is free of dust, so that no abrasion of the blades can occur.

When the air is used in a closed circuit, it is drawn through the air separator, as before, and then passes through the fan carrying the finished material in suspension. Then it is blown into a cyclone collector, which recovers part of the finished material, the finer dust being returned to the mill with the air, as in the ring-roll mills.

As most of the system is under a slight vacuum, air leaks into it and a corresponding amount of air must be vented beyond the fan and may be filtered through tubular bags. This portion of the air may be increased by drawing some fresh air through the mill and this practice will be beneficial in removing the heat generated and the moisture released during pulverizing.

Pulverizing Anthracite Slush.—Red-ash anthracite slush from the Lykens Valley mines has been ground in ring-roll mills quite readily and without undue wear. This coal is essentially a semi-anthracite which occurs at the southern end of the coal fields and is of lower rank than most Pennsylvanian anthracite. The white-ash coal mined in most of the anthracite fields has been found more difficult to pulverize. Any type of mill must be operated at a reduced capacity and the pulverizing elements must be made of materials which will resist abrasion as much as possible.

The plants in the anthracite district which have been experimenting with pulverized fuel, are making comparative tests of the various types of mills for grinding slush. Within the next year or so several types of tube mills and conical ball mills will be installed and tried out in this service. All of these mills will probably be air-swept and will operate on closed circuit grinding (see also page 597). A preliminary investigation was made by the engineers of one of the plants now using pulverized anthracite. According to O. M. Rau,* "the various

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* "Burning Anthracite Mine Waste Efficiently," *Power*, **54** (1921), 828.

attempts to pulverize anthracite were analyzed and the action on mills of the ring-roll, tube and pebble types was noted, with the result that it was found to be commercially feasible on a basis of a mill capacity of one-half that obtained with bituminous coal and with about double the maintenance expense."

Bituminous Coal.—Tube mills are used for pulverizing coal in many cement plants, especially where this type of mill is also used for grinding cement materials. They are all operated on open-circuit grinding with displacement discharge and, consequently, operate under a disadvantage as compared with the possibilities of air-swept mills grinding in closed circuit. In the cement industry there has been no special incentive for the application of air sweeping to tube mills pulverizing cement clinker. It has been tried, but open-circuit grinding has been found more suitable because the proportion of extra fine material produced aids in the rapid setting of the cement. Pulverized coal forms only a minor product in a cement mill. In a power station, however, if pulverized bituminous coal is to compete with mechanical stokers, every possible economy must be effected in connecton with its preparation and a simple plant is desirable. The following are the good points of tube mills:

1. They require but little attention and can be operated by unskilled labor.
2. They have no internal mechanism; hence the cost of maintenance is low and they are not damaged by tramp iron which may be fed along with the coal.
3. The wear of the grinding elements is compensated for by adding at intervals a certain proportion of new balls or slugs with the feed.
4. The mill may be relined without dismantling, a manhole being provided for dumping the charge and gaining access to the interior.
5. They can be built in units of larger capacity than other types of mills.

While the tube mill is inherently a simple machine to operate, there are many factors which must be taken into consideration in order to obtain efficient grinding. It should be so operated as to secure the most economical combintaion of the factors of weight and fineness of output, power consumption, cost of maintenance, and the cost of the grinding elements per unit of output. Many tube mills are being operated without much regard to obtaining an economic balance between these factors. When once adjusted for economic operation, the tube mill can be operated with very little attention.

Operating Tube Mills on the Unit System.—Some experiments are being made in one or two large steel mills with a view to using pulverized coal for firing boilers, as an auxiliary fuel, during periods of relatively short duration when blast furnace gas is not available. Blast furnace gas will be available most of the time and will furnish most of the fuel requirements after certain improvements have been made in the steam plant and electrical equipment, which will gradually reduce the steam requirements Owing to the limited use which will be made of the pulverized-coal equipment, it is necessary to install a type of plant which will require only a moderate initial investment and low operating charges.

The experiments are being made with tube or ball mills operating on the "Unit System." An individual air-swept mill is installed in front of each boiler (of about 250 rated horsepower). The coal will be trammed to each mill without drying and with no opportunity for removing tramp iron. This type of mill is the only one which is not subject to damage from the introduction of tramp iron. They are also sufficiently simple and rugged to be operated by the regular firemen, and this elimination the necessity for a central milling plant and conveying system with a separate operating force.

The Smidth tube mill is used in a number of cement plants for grinding coal. The distinctive features of this mill lie in the heads and in the grinding elements. The heads are of cast steel and, for most materials, the outlet is located in the periphery. This is claimed to give a better efficiency than can be obtained with central outlets.

While flint pebbles are used for grinding a few materials, the more commonly used elements are known as "cylpebs." These are of cast metal, cylindrical in form and, according to the use to which they are to be put, are either ½ by ⅝ in. or ⅝ by 1 in. in dimensions. The use of the proper size of cylpebs entirely overcomes the tendency of some bituminous coals to be pressed together into flakes in the process of grinding, as previously mentioned.

F. L. Smidth & Co. advocate the three-stage reduction process (as outlined on page 571, in connection with the theory of grinding) and recommend that the three stages be carried out in separate machines in order to secure the maximum efficiency. The type of ball mill built by this company for granulating the material, in preparation for finishing in a tube mill, is known as the "Kominuter." This is fitted with conical screens mounted on the exterior of the cylinder. One type of screen entirely surrounds the drum and the material leaving the mill flows back from the smaller to the larger end of the cone, where the coarse material is returned for regrinding after the fine material has passed through the screen. Another type, known as "fasting screen," is made in the form of small cones and a number of these are mounted at equidistant points on the periphery. Roughly speaking, the power requirements for the two machines vary from 20 to 30 hp.-hr. per ton of coal. A plant in New York State is equipped with a No. 53½ Kominuter and a No. 16 Cylpeb tube mill. These require 30 hp. and 100 hp., respectively, and are operated together for 11½ hr. with a daily output of 75 tons of coal, or 6.5 tons per hour. This corresponds to a power consumption of 20 hp.-hr. per ton, or approximately 17 kw. hours of electrical input to the motor.

In a plant in Kansas a No. 66 Kominuter and a No. 18 tube mill are pulverizing 7 tons of coal per hour. In a Canadian plant a No. 85 Kominuter is grinding from 15 to 20 tons of coal per hour to pass a 1⁄16-in. mesh screen.

The Allis-Chalmers Compeb mill is shown in Fig. 127. This mill is of the two-stage type and a patented form of grinding body is used in the finishing compartment, known as "Concavex." These are not complete spheres but are cast with a pair of concave zones on opposite sides and are made from a special white alloy-iron which is resistant to wear. The diameter, when new, is 1¼ in. The concave and convex surfaces nest together and secure greater contact area. This, it is claimed, makes it possible to secure either a finer product, or a greater capacity, from a given mill.

The division head, between the coarse and fine grinding compartments, carries a grid for holding back coarse material and a set of spirals for advancing the fine material to the lifters which discharge it through the center of the head. The discharge from the finishing compartment passes through a radial screen plate of manganese steel, in which are slotted holes, ¼ by 4 in. These plates hold back the grinding balls and allow the product to be picked up by eight lifters and discharged through the trunnion.

This mill is built in several sizes, ranging from 3.5 to 8 ft. in diameter, and from 14 to 26 ft. in length. When grinding coal to a fineness of 85 per cent. through 200-mesh, the capacities range from 1½ to 25 tons per hour and the power required is approximately 22 hp.-hr. per ton. This is equivalent to an electrical input of about 18.5 kw.-hr. per ton. Coal may be fed to the mill containing lumps as large as 2 or 3 in. These are crushed in the first stage by forged-steel balls, 5 in. in diameter. These may be left in the mill until they have worn down to about one-half of this diameter.

The compeb mill operates on open circuit with displacement discharge. The Allis-Chalmers Co. is building an experimental type of air-swept mill to operate on open-circuit grinding, which is known as the "Triturator." This mill will have three division heads, the four compartments being charged with successively smaller balls or concavex. The air will be used on open circuit and will be filtered through tubular cloth bags. The first unit will be installed in a mine power plant by M. A. Hanna & Co. for pulverizing anthracite slush.*

The Kennedy-Van Saun tube mill† is shown in Fig. 130, equipped to operate with air separation. In the more recent design the trunnion discharge openings have been greatly enlarged in order to facilitate the use of air for removing finished material. This mill is operated at cascading speeds; the charge is then in an open state and can be thoroughly penetrated by the air current, which removes the finished material as rapidly as it is ground to the required fineness. Certain practical difficulties have had to be overcome, before this could be accomplished successfully, as has been done by this company in the case of a mill 4 ft. in diameter. This method is to be applied to some large mills which will be installed in some boiler plants for pulverizing anthracite.

The grinding bodies are forged-steel balls of 2 in. diameter in the head end and 1½ in. in the finishing end. The latter may wear to ⅞ in. diameter. The 2-in. balls will crush 1¼ in. lumps of coal. Two-inch lumps may be fed to the mill by

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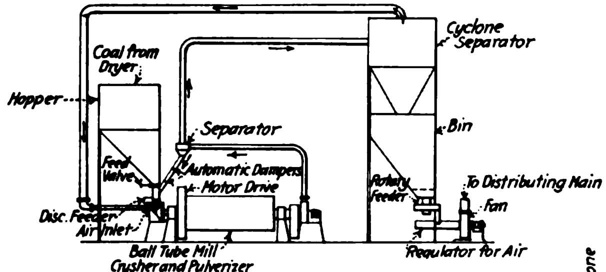
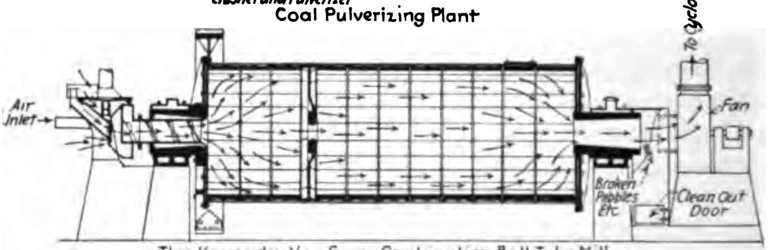
* The authors are indebted to E. C. Greisen for information.

† The combination ball-tube mill was originally patented by J. E. Kennedy about the year 1909.

using larger balls, but it is considered more economical to reduce the raw coal to the smaller size in roll crushers than in a ball-mill compartment with the larger balls. The granular product of the first stage is elevated by the lifters on the division head, which advance it through the central opening to the finishing compartment. Some 200-mesh material will be produced in the first stage and this will be carried out of the machine, by the air current, along with the product of the second stage.



Coal Pulverizing Plant



The Kennedy-Van Saun Combination Ball Tube Mill

FIG. 130.—The Kennedy Van-Saun combination ball tube mill.

As 1½-in. balls are heavy enough to crush ½-in. lumps of coal, it is claimed that a single-stage tube mill with air separation may be fed with bituminous coal which has been crushed to this size. While accurate data on output are not available, it is expected that the small sized mill, 4 ft. in diameter by 6 ft. long, should have an output of between 3 and 4 tons per hour ground to the usual fineness. Mills of 7 or 8 ft. diameter have a normal output of 25 tons per hour, or more, and this should be increased by the use of air. The crushing of coal in single and double rolls in series is mentioned on page 558. By this means it may be reduced to ⅜ in. and finer for feeding to a single-stage air separation tube mill.*

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* The authors are indebted to J. E. Kennedy and H. A. McGraw for information.

The Hardinge conical mill is built with a short cylindrical section in the middle and with conical ends. The feed end is only slightly conical, while the discharge trunnion is located at the apex of a long cone. The peripheral velocities are, therefore, graduated. When the charge is being cascaded in the cylindrical portion, the material in the cone is merely being tumbled. It is claimed that larger balls slide down the lower side of the cones and displace the smaller balls which migrate into the long cone.

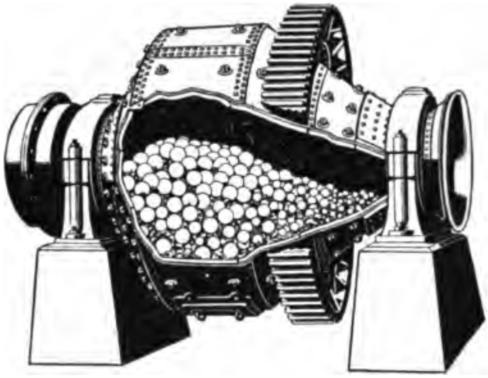

FIG. 131.—Hardinge conical mill, with section showing tendency of balls to segregate according to size.

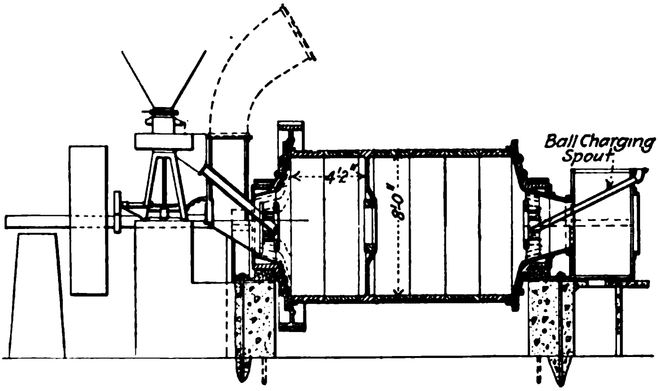

FIG. 132.—General arrangement of 8 ft. × 12 ft. air-swept combination tube mill.

Thus, an automatic classification of the balls is effected without division heads and the larger balls crush the incoming lump material in the cylindrical section, while the smaller balls crush the finer material as it passes through the cone on its way to the discharge trunion.

For fine grinding, the balls in a new charge vary from 3 in. to 1.5, and replacements are made by introducing a few 3 in. balls daily. The mills are operated at a tumbling speed for the cylindrical end, although cascading speeds are used for the coarse grinding of some materials. These mills are operated in closed circuit with an air separator, in some installations, most of the oversize being handled and returned mechanically. The air separation system has been used for several years for grinding quartz.

A few conical mills now being tested for grinding anthracite slush. Future installations for grinding coal will probably be equipped to operate in closed circuit with an air separator or a vibrating screen. The mills are built with cylindrical sections ranging from 3 to 10 ft. in diameter and from 8 in. to 3 ft., or more, in length. Coal should be crushed to 1-in. size, or smaller, before grinding in a single-stage mill.*

Pulverizing Elements.—In addition to the elements made by the mill manufacturers, special balls and lining plates are made for tube mills by other companies. A cast-composition ball, known as "manganoid" is made by the Jeffrey Manufacturing Co. This ball is resistant to abrasion and, consequently, has a long life. A patented form of chilled-iron plate for lining tube mills, which is widely used, is made by the Fuller-Lehigh Co.

Air Separators.—Several air separators are available for closed-circuit grinding, one of the best developed being the Clark separator. This is a centrifugal type with special internal baffles and is operated by suction. A very close classification of sizes can be effected and a product of any desired degree of fineness secured, all oversize material being returned to the mill for grinding.

The only installation, at the time of writing, where the dry milling of coal has been carried on for some time in a tube mill operating on closed circuit, is at the Decatur Atomized Fuel Co., Decatur, Ill. The Decatur rod mill is equipped with a Clark separator. This is a cylindrical mill, about 5 ft. in diameter, charged with forty 3-in. steel rods, 10 ft. long. As previously noted, several other installations are being equipped with various makes of ball and tube mills for grinding anthracite in closed circuit with an air separator.

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* The authors are indebted to H. Hardinge for information.

Vibrating Screens.—Another type of classifier, which is being tried in connection with the dry milling of coal in ball mills, is the "Hummer screen." This has been developed by the V. S. Tyler Co., Cleveland, O., for screening finely divided materials, and it is being used in connection with the grading or pulverizing of minerals, ores, fertilizers, cement materials, abrasives, etc. The screen is inclined at an angle with the horizontal of from 24° to 35°, and is installed in a dust tight casing. It is of woven iron wire and is stretched taut on an adjustable frame by means of screws operated by hand wheels. Above each screen an electromagnetic vibrator is mounted. These are excited with alternating current, supplied by a special generator at a frequency of 15 cycles, and they are provided with a hand wheel for accurate adjustment with respect to the degree of vibration. The vibration causes the material to spread immediately upon coming in contact with the screen. The intensity of the vibration produces a sorting action by tossing the larger particles away from the screen, while the fine material, in travelling down the incline, remains in contact with the screen until it passes through.

Dust Extractors.—The tubular cloth filters form a much more compact installation than the old fashioned bag filters, which are not practicable for coal-milling plants. As previously noted, tubular filters are coming into frequent use for collecting fine coal dust from the vent tubes on the air-circulating system for Raymond mills. The tubes are shaken automatically every few minutes and the dust dropped into the hoppers. This type of filter is also used where the air-sweeping of the mill is effected on open circuit, although the filters must then be large enough to pass all the air used. Filters of this type are manufactured by the Clark Dust Collecting Co., Chicago; by the Dust Recovering and Conveying Co., Cleveland and by the Allis-Chalmers Co., Milwaukee.

A centrifugal type of dust extractor is being developed by By-Products Recoveries, Inc. (New York), which is capable of recovering a very high percentage of the fine dust from blast-furnace gas and smelter gases. Smelter fumes, and gases from some types of metallurgical furnaces, often carry metallic vapors which sublime, on cooling, into extremely fine particles of copper, silver and other metals, and these can be recovered without the use of cloth bags or filters.

This apparatus is known as the Taylor-Milliken dust extractor and resembles a steam separator as regards the spiral which gives the gases a rotary motion as they pass through a cylindrical space. The central spiral is vertical and is built of steel plate, surrounded by a cylindrical grid of round wire about 3/8 in. in diameter. This is wound with the intervals between the wires, about 1/16 in. wide. This wire grid is surrounded by a series of dust chambers, one above another, in which there is no movement of the gas. The dust is expelled from the rotating gases centrifugally and passes through the grid into the quiet spaces, where it settles and is drawn off at intervals.

In one test about 97 per cent of the dust was removed from blast-furnace gas, and similar efficiencies have been attained with dust from other sources. This type of extractor should be applicable to the cleaning of large volumes of gases carrying coal dust from pulverizing mills and dryers, as well as for extracting fine ash from furnace gases where pulverizd coal is burned. Much of the coal dust is coarser than dust which has been collected in the tests so far made and a recovery of practically all the coal should be possible where the air is used in open circuit for air-sweeping the mills.

Cost of Preparation.—The cost of preparing pulverized coal naturally varies with the kind of coal, the moisture content, size of plant, load factor of operation, type of equipment, etc. Muhlfeld states* that the smallest size of plant worth considering for pulverizing coal for boilers would have an output of 80 tons per day. Where the competition with other fuels is close, as in burning high-grade bituminous coal on stokers, a 200-ton plant might better be considered as a minimum economical size.

A milling plant having an actual daily output of about 200 tons of coal for use in a metallurgical plant, reports an average cost, over a period of 6 months, of $1.05 per short ton for preparation and conveying. This includes all fixed charges on the investment, as well as operation and maintenance. Another plant with a considerably larger output reports that the cost of operation and maintenance ranges from 75 to 80 cts. per ton. This includes the cost of handling, preparing, conveying and firing, as well as the cost of tramming the coal to the plant and dumping it, which item is about 10 cts. This leaves the cost, beyond this point, 65 to 70 cts. per ton, exclusive of the fixed charges on the

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* "Powdered Coal," by JOHN E. MUHLFELD, *Proc. Eng. Soc. W. Pa.*, May, 1920.

investment. In both of these plants ring-roll mills were used. The figures for the first plant were for 1920; and for the second, for 1919.

These plants were both installed a good many years ago and it is well to examine an estimate on the cost of pulverizing coal in a modern plant. Two examples are taken with daily outputs of 500 and 1,000 tons, respectively, using 57-in. Fuller mills having a capacity for pulverizing 8 tons of bituminous coal per hour to standard fineness. This is the largest ring-roll mill built for grinding coal. The unit costs for power, labor and dryer coal are assumed by the author, the remaining data being furnished by the Fuller Engineering Co.

The following table contains data on the capacity, cost, etc., of milling plants contianing four and seven mills, respectively.

Number of 57-in. mills installed	4	7
Number of mills in operation (allowing a spare unit)	3	6
Daily output of plant (in tons of 2,000 lb.)	500	1,000
Number of hours required:		
At 7 tons per mill per hour	24	24
At 8 tons per mill per hour	21	21
Size of dryers (2 units)	5½ × 42 ft.	6½ × 50 ft.
Size of building	40 × 128 ft.	40 × 160 ft.
Cost of Installation:		
Building	$ 25,000	$ 28,000
Machinery	175,000	240,000
Total	200,000	268,000
Annual fixed charges at 15 per cent	30,000	40,200
Daily fixed charges for 330 days (assuming half-time Sundays)	$90.90	$121.81

The installation costs are of July, 1921, and include Fuller-Kinyon pumps and 200 ft. of pipe for transporting the coal to the furnace bins.

When operating continuously, the mills will need to grind only about 7 tons an hour for a daily output of 500 tons. An output of 8 tons per mill will reduce the time required to approximately 21 hours daily operation, the remainder of the time being available for repair work by the operating force. With four units in operation, and grinding 7 tons of hour, 500 tons can be ground in 18 hours. With an output of 8 tons an hour, only 16 hours will be required. Hence there is a possibility of operating the 500-ton plant on a two-shift basis, provided the maintenance work is done on the third shift. It is advantageous to provide a storage bin between the crusher and driers of sufficient capacity to enable the crusher to do its daily work in ten hours.

The operating force is these plants would be made up as follows on each shift:

Output of plant, tons	500	1,000
Number of shifts	2 or 3	3
Miller and helper, each, hours	20	21
Dryer fireman, hours	20	21
Crusherman and helper, each, hours	18	16
Additional helper, hours	...	20
Total labor hours	96	115

When the 500-ton plant is operated on two shifts with four mills running for 16 or 18 hours daily, an allowance of 20 hours is made for contingencies. Hence the millers and fireman would work in two shifts of 10 hours and the crushermen in two shifts of 9 hours. By crushing all the coal in 10 hours, as suggested, two crushermen only would be required for a single 10-hour shift. The labor required for maintenance is not included in the foregoing; hence it would be possible to employ all the operatives on shifts of equal length by having them do repair work when their machines are not running. This would also apply in the case of the 1,000-ton plant when the miller and fireman and additional helper are employed in three 8-hour shifts.

Labor is figured at 55 cts. an hour, including 50 cts. for helpers, 65 to 70 cts. for mill foreman, and a small allowance for superintendence.

The cost of drying will be offset, in part, by the improvement in the net calorific value of the fuel, since the moisture must be evaporated in the furnace when burning raw coal. The usual efficiency of the Fuller dryer is about 6 lb. of moisture evaporated per pound of coal fired. The proportion of coal consumed for drying the remainder ranges from 1 to 1.5 per cent when the moisture content is 7 per cent.

OPERATING COST DATA ON COAL MILLING PLANTS

Capacity of plant, tons per day	500	1,000
Equipment, number of 57-inch mills	4	7
Labor hours, daily, in 8-hour shifts	96	115
Dryer coal	7	14
Power, 14 kw.-hr. per ton	7,000	14,000

Daily Plant Costs

Power, at 1.5c. per kw.-hr.	$105.00	$210.00
Dryer coal, at $7 per ton	49.00	98.00
Labor, at 0.55c per hour	52.80	63.25
Maintenance, at 7c. per ton	35.00	70.00
Fixed charges	90.90	121.81
	$332.70	$563.06
Cost per ton prepared	$ 0.666	$ 0.563

If the demand for coal falls off during part of the year, the cost per ton will be somewhat higher, and this will also be true if the plant is operated regularly with a smaller daily output. The following tables indicate the effect of operating the plant at load factors of 70 per cent and of 35 per cent, the outputs in the previous tables being taken as 100 per cent load factor. These factors are based on the operation of the plant with two shifts and with one shift, respectively, of 8 hr. each. Maintenance work that cannot be done during operating hours can be done in the idle periods, and this will allow of more continuous operation during the working shifts. In the case of the 500-ton plant, 66.6 per cent labor has been assumed for 70 per cent load factor and 33.3 per cent labor for 35 per cent load factor. In the 1,000-ton plant the percentage of spare equipment is less than a larger percentage of labor hours has been assumed for 70 per cent load factor. In spite of this, 96 labor hours may produce 700 tons in two 8-hour shifts in the larger plant, as compared with 500 tons in two 10-hour shifts, or in three 8-hour shifts in the smaller plant.

MILLING PLANTS OPERATED WITH LOAD FACTORS OF 70 PER CENT

Output of plant, tons per day	350	700
Labor hours, assumed (two shifts per day)	64	96

Daily Plant Costs

Power	$ 73.50	$147.00
Dryer coal	34.30	68.60
Labor	35.20	52.80
Maintenance	24.50	49.00
Fixed charges	90.90	121.81
	$258.40	$439.21
Cost per ton prepared	$ 0.738	$ 0.627

MILLING PLANTS OPERATING WITH LOAD FACTOR OF 35 PER CENT

Output of plant, tons, per day	175	350
Labor hours, assumed (1 shift per day)	32	48

Daily Plant Costs

Power	$ 36.75	$ 73.50
Dryer coal	17.15	34.30
Labor	17.60	26.40
Maintenance	12.25	24.50
Fixed charges	90.90	121.81
	$174.65	$280.51
Cost per ton prepared	$ 1.00	$ 0.80

COAL CLEANING

When coal contains a considerable proportion of mineral impurities, it is often desirable to clean it before subjecting it to further preparation, such as pulverizing or distillation. The more finely it is crushed or granulated before cleaning, the greater the proportion of the foreign matter which may be removed by effective processes. Since coal is always crushed or granulated before pulverizing, briquetting or coking, or before being distilled at low temperature, there is an excellent opportunity for cleaning it by washing or other means.

Coal cleaning operations in America are largely confined to the prepared sizes of coal for domestic and other uses, and to coal used for coke manufacture. Cleaning operations are usually applied near the mines to coal which has been previously classified into fairly uniform sizes. Bituminous steam coals, however, are usually shipped as a run-of-mine product without cleaning, and the grade of the product is dependent upon the care exercised by the miners to load only good coal and to leave the rock in the mine.

Many of the Appalachian coals are normally low in ash, but, during the last few years, the labor available at the mines has been growing less efficient and pieces of slate, shale and bony coal, from partings in the vein or from the roof or floor, are being shipped with the coal. To cite an example: A central station company in a large city obtains coal from its own mine in West Virginia. The coal from this mine, when carefully prepared, shoud run about 6 per cent. in ash. Recently, due to inefficiency of labor, the coal has been running as high as 15 to 18 per cent ash.

Effect of Ash in Steam Coal.—Excessive quantities of ash increase the costs of transportation, and of handling fuel and ash at the plant, and they reduce the capacity and efficiency of the boilers, especially when the coal is burned on grates or stokers. This is clearly summarized by J. E. Muhlfeld as follows:*

Exclusive of moisture, commercial steam coals contain from 5 to 25 per cent of impurities, which means that, out of every ton of 2,000 lb., from 100 to 500 lb. has practically no heat value and is, further, detrimental.

For all practical purposes, the eight principal impurities that occur in coal may be generalized as follows:

MATERIAL	PERCENTAGE OF TOTAL IMPURITIES.
Silica	25 to 55
Alumina	15 to 35
Iron	10 to 30
Sulphur	trace to 5
Calcium	trace to 5
Potassium	trace to 3
Sodium	trace to 2
Magnesium	trace to 2

These impurities come from three sources— vegetable material; clay, sand, or shale; and extraneous substances— and combine to form a mechanical mixture of silicates, oxides and sulphates. With the exception of sulphur, which is an undesirable element and occurs as iron pyrites or calcium sulphate, all are non-combustible. In general, the silica, alumina, and magnesium content will tend to decrease the fusibility of the impurities in the coal.

The clinkering and honeycombing of the impurities in coal is one of the most destructive results of combustion where fuel is burned on metal surfaces, and its formation may be either chemical or by adhesion or fusion of particles of ash and combustible into slag. Roughly, each 1 per cent of impurities causes a decrease of from 0.5 to 1 per cent in combustion efficiency, and from 1 to 1.5 per cent in boiler capacity. As practically all the oxygen disappears at a few inches above the grate, this applies particularly where agitation of the fuel bed mechanically mixes the impurities with the combustible and converts the former into the more fusible ferrous silicates, with resultant clinkering and honeycombing.

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* "Powdered Coal," by J. E. MUHLFELD, Vice-president, Railway & Industrial Engineers, Inc., New York, *Proc. Eng. Soc. West. Pa.*, May, **1920,** 243.

The tendency of coal to clinker varies almost directly with the content of iron pyrites and inversely with the ash content. When the ash is low in relation to the sulphur content, clinkering is usually extremely bad unless a cooling process, or a counteracting agent such as limestone, is applied to the grates to prevent fusing of the clinker thereto. The pyrites, which is the principal slag-forming material in coal, when reduced to ferrous sulphide, passes into a molten state at about 1,165 C. (2,150°F.); and, in combination with the ash, forms layers of solid clinker on top of the grates and stops the passage of the air. The result is that the grates become over-heated and cause the clinker to melt and flow through the grate openings. This results not only in clogging and warping the grates, but also in their corrosion and destruction, due to the sulphur combining with the overheated metal.

While the sulphur itself has little to do with the fusibility of the ash, the iron, combined with a part of the sulphur, does. In general, the greater the percentage of iron, the more fusible the slag. Furthermore, fused ferrous sulphide fluxes aluminum silicate and also causes clinker. With the grates clinkered, there is insufficient air for complete combustion, with the result that ferrous oxide is formed and unites with the silica to form honey-comb, which becomes very fusible at temperatures over 1,300°C. (2,400°F.), and will tend to adhere to those portions of the boiler metal and furnace refractories where the temperature is highest.

Thus we find that, due, primarily, to lack of air supply through the metal work, on which the fuel bed is placed, we have the cause of both clinker and honeycomb in the production of ferrous sulphide and ferrous oxide, respectively, which, in turn, have a most destructive effect not only on the metal work, which is responsible for the restricted air supply, but on the refractory surfaces as well.

When coal is properly prepared and burned in powdered form, the usual difficulties resulting from clinker are eliminated, as there are no grates or retorts on which it can accumulate, and it cannot interfere with the air supply requisite for combustion. However, with coal that contains certain intrinsic combinations of ferrous silicates which fuse at relatively low temperatures 1,100 to 1,250°C. (2,000 to 2,300°F.), honeycomb formation will result unless the proper fuel, air, and draft regulations obtain to convert the ferrous sulphide into ferric oxide, which is the result of complete combustion and requires 50 per cent more oxygen or dry air to produce than ferrous oxide. For this process an oxidizing atmosphere must at all times obtain in the combustion chamber in order to prevent the reduction of ferric sulphide to ferrous sulphide, and, as the burning of fuel in suspension is not dependent upon the air supply through openings that are liable to become clogged, this can easily be provided.

The author would add that, while the difficulties encountered when burning coal on grates are avoided by burning it in pulverized form, there is a new set of problems encountered in connection with the disposal of the ash and slag. Coal can be more effectively cleaned, however, when finely divided, and this factor may be taken advantage of in connection with the preparation of pulverized fuel.

Preparation of Coal for Coking.—Most of the bituminous coal washed in the United States (Table XXVII) is slack for making coke, and more than half of the total tonnage is Alabama coal.

A few of the best coking coals, notably those from the Connellsville district in Pennsylvania, require no special preparation or cleaning. The supply of such coals, however, is very limited and most of the available coals are much improved by cleaning before coking. The picking table and the Bradford breaker are simple devices, but often the impurities are of such a nature that the coal has to be washed.

Many devices are used for washing since different coals require different treatments. The specific gravities of both the coals and the impurities differ markedly, also the manner in which the two are associated, and the latter factor largely affects the size to which the coal should be crushed before washing. The most effective sizes vary from nut to granulated. When the sulphur is contained in definite strata of pyrite, a large part of the pyrite is crushed to dust of flake form. If the coal is too finely crushed, this remains in suspension in the washer and goes over with the coal.

It is often found advisable, therefore, to wash the larger sizes and then recrush to the degree of fineness which experience shows will give the best results in coking that particular coal.

Sulphur is the most objectionable impurity and it occurs most commonly as:

1. Iron sulphide (FeS_2), either, as pyrite or marcasite.
2. Calcium sulphate (gypsum).

Sulphur in the form of sulphide is largely eliminated in the coking process, but the sulphate remains in the coke.

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"Metallurgical Coke," by A. W. Belden, U. S. Bureau of Mines, *Tech. Paper* **50**, 1913.

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Domestic Fuel and Slack.—Where bituminous coal is classified by sizes at the mines for use as domestic fuel, and for other purposes, the various commercial sizes are sometimes cleaned by jigging or other means.* The final screenings, or slack, is also cleaned and sold for low uses. This is often used for making pulverized fuel.

Anthracite Industry.—In the early days of the anthracite industry the slate and rock which were mined with the coal were picked from the larger sizes by hand, but, with the enormous increase in production and the high cost of labor, it became necessary to develop mechanical means for separation. The only principles of operation available were the difference in gravity and the difference in frictional resistance as the coal and rock slid down a chute. The dry processes were among the first employed and they are still used to a considerable extent. Today, the greater part of the coal produced by the larger companies is cleaned by the wet processes, including the use of jigs similar to those used in metal mining.

With the exhaustion of the virgin seams of coal probably 40 per cent of the anthracite now mined in the northern district is coming from seams less than 30 in. in thickness. This means that an increased ratio of slate, rock and fire clay are coming to the surface and the coal must be washed in order to remove the fireclay and its discolorations.

Heretofore, there has been but little attempt made to carry the cleaning of the coal down into the steam sizes, although these benefit by the cleaning of the larger sizes to some extent.

These sizes are classified by passing them through a series of

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* Consult: *Univ. of Ill., Eng. Exp. Sta. Bull.*, **69**, "Coal Washing in Illinois," by F. C. Lincoln, 1913.

shaking screens, mounted one above the other, during which operation they are drenched with a water spray. The water carries the small coal down through the screens and washes off clay and sand. These impurities go into the final screenings, which are usually known as slush or silt. The increased ratio of rock makes it desirable to clean the steam sizes before shipment, in order to reduce the cost of transportation and to utilize the available supply of cars to the best advantage.

At most of the collieries only three buckwheat sizes are prepared. Some, however, are preparing No. 4 buckwheat, or "birdseye," from the slush by classifying it by hydraulic methods. The fine silt is rejected, and with it go most of the impurities. More attention is now being paid to the cleaning of the slush.

The economic radius, within which silt from the culm piles can be utilized in pulverized form, is largely dependent upon the facility with which it may be cleaned before shipment. As indicated in Table XXVII, considerable refuse coal from old culm piles is being put through the washeries to recover marketable coal ranging from the domestic sizes of No. 4 buckwheat. In addition, considerable quantities of river buckwheat are being dredged from the rivers into which the fines from the breakers were formerly allowed to drain. This industry is now being carried on to an extent which may exhaust this sources of coal in 8 or 10 years.*

Cleaning Coal for Further Preparation.—As mentioned on page 446, the cleaning of coal for distillation at low-temperature increases the yield of by-products and also the value of the carbonized fuel. Preliminary cleaning will increase the output of prepared fuel from all types of preparation plants and will effect economies of power in pulverizing. The reduction in the ash content of pulverized coal will widen its field of application in industrial furnaces where it must compete with gas or oil.

The effective cleaning and preparation of low-grade fuels will often render local fuel resources available for use in regions where high-grade fuels can only be obtained by transportation from a distance. This is especially true in the case of some of the countries of South America which were formerly dependent upon English coal. Owing to the restriction of exports of English

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* Estimate by Pennsylvania Geological Survey. Reference: "The Preparation of Anthracite," by P. Sterling, *Trans. Min. Eng.*, **1911**, 264.

coal, they are now largely dependent upon American coal (see page 682). The utilization of domestic resources in foreign countries will also relieve our transportation facilities of the hauling of coal to the seaboard for export and will conserve our own resources.

The principal processes which are used for cleaning coal, or which are applicable hereto, are tabulated in Table LXXXV, together with the principle of operation. Of the various washing processes used, only the more important are included.

TABLE LXXXV.—PRINCIPAL COAL-CLEANING PROCESSES

TYPE OF PROCESS	OPERATES BY THE DIFFERENCE IN	KIND AND SIZE OF COAL
Dry processes:		
Bradford breaker	Brittleness	Lump bituminous
Chute with slot	Friction	Lump anthracite
Spiral chute	Friction	Lump anthracite
Inclined belt	Friction	Lump anthracite
Electrostatic	Electrical conductivity	Fine coal
Wet processes:		
Spraying	Rinsing	Lump or fine
Settling tank	Free settling	Lump or fine
Dorr classifier	Free settling	Fine coal
Inverted cone	Hindered settling	Fine coal
Piston jig	Hindered settling	Lump coal
Pan jig	Hindered settling	Lump coal
Bumping table	Hindered settling	Lump or fine
Chance process	Sand flotation	Lump or fine
Trent process	Oil amalgamation	Pulverized

Several of the dry processes have already received passing mention. One new one, suitable for cleaning fine coal, remains to be described more at length.

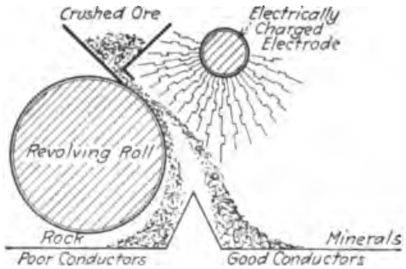

FIG. 133.—The separation of ores by electricity.

The Electrostatic Process. This process has been developed by the Huff Electrostatic Separator Company, of Arlington, Mass., for the separation of particles of electrically conducting minerals from non-conducting rock particles. It is being used commercially for concentrating ores of zinc, titanium and other metals, and for concentrating graphite which occurs disseminated in small flakes in granitic rocks. The process is also being used for the recovery of fine particles of high-speed tool steel from carborundum dust, the mixture resulting from the grinding of tools. It has been applied experimentally to the cleaning of bituminous coal and anthracite.

The material must be crushed to granular size, ¼ in. and smaller, with a minimum proportion of dust. It must also be dried in order that the particles shall not tend to adhere to one another and will flow readily through the machine. The presence of moisture increases the electrical conductivity of the material and its removal is necessary to differentiate the conductivity of the constituents to the fullest extent. As in washing coal, it is desirable to grade it by screening into two or three sizes which may be treated separately.

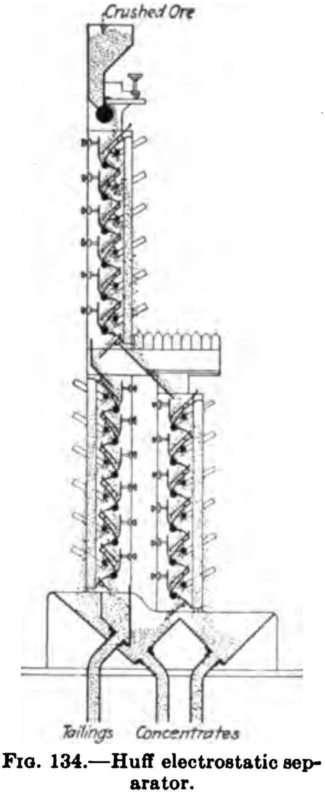

FIG. 134.—Huff electrostatic separator.

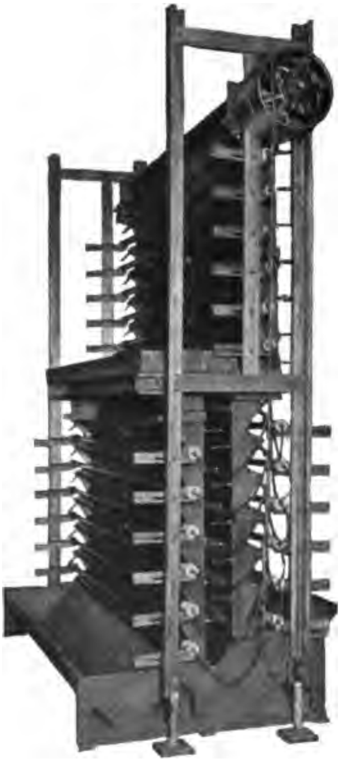

FIG. 135.—Huff electrostatic separator exterior view.

The material is fed through a hopper and allowed to cascade over a series of metal chutes (Fig. 134, 135), the stream falling in front of an electrode. This is a steel bar, mounted parallel with the apron which forms the edge of the chute, and is charged with a high voltage of continuous polarity, the opposite side of the circuit being grounded to the chutes. The coal falls between the two and the stream is divided by the selective attraction of the electrostatic field for the more conducting particles.

In the cases of anthracite from Pennsylvania and subbituminous coal from Brazil, the coal particles are attracted more strongly than the slate, shale and pyrite. The pyrite is a conductor and will be drawn over if too high a voltage be used. By proper adjustment of the voltage and the electrode spacing, most of the pyrite goes with the refuse. In the case of bituminous coal from Pennsylvania, the coal particles are non-conductors, while the carbonaceous slate and the pyrite are conductors and are attracted by a sufficient voltage.

Recently, some experiments were made with anthracite dredged from the Susquehanna River having an ash content of from 30 to 40 per cent. This was reduced to about 15 per cent by the removal of sand particles, while the coal was almost all recovered.

A small sample of anthracite slush from the northern district was treated with the following results:

	Weight of Coal, Per Cent	Ash, Per Cent
Original	100.00	17.00
Concentrates	85.63	11.00
Middlings	10.87	41.00
Tailings	3.50	61.00
Totals	100.00	

Another sample tested was bituminous coal taken from a carload shipped from Coal Glen, Pa. This was graded by the electrostatic machine into high and low-grade fractions, as indicated in Table LXXXVI under analyses Nos. 2, 3, and 4.

The proximate analysis of the low-grade fraction (4) indicates that it has a good thermal value and this is confirmed by other tests, made by the Huff Co., in which the calorific value of the low grade fraction was measured. In the above test the only measurement of calorific value was made on the high-grade fraction (3) and this was compared with the original

TABLE LXXXVI.—TEST OF ELECTROSTATIC GRADING OF COAL

Proximate analyses of	Per cent of total	Moisture	Volatile	F. C.	Ash	B.t.u.	Sulphur
1. Sample from same car	.....	0.74	29.5	56.7	13.8	13,152	3.02
2. Sample graded	100.0	0.90	33.2	53.5	13.1	......	3.35
3. High-grade fraction	73.0	0.96	35.8	56.6	7.6	13,869	1.22
4. Low-grade fraction	27.0	0.72	25.9	44.6	29.2	......	9.1
Second grading of low-grade fraction							
5. Middlings	15.5	0.88	28.6	45.4	26.0	......	4.35
6. Tailings	11.5	0.50	22.0	44.0	34.0	......	15.52

measurement on another sample (1), taken from the same car, which has a slightly different proximate analysis.

The low-grade fraction was passed through the separator a second time and graded into middlings (5) and tailings (6). In the latter case a considerable concentration of sulphur was evident in the form of yellow pyrite crystals, which had a greater electrical conductivity than other constituents of the coal. The concentration of the ash in the low-grade fractions must also be due to the conductivity of the elementary carbon and the iron oxides in the particles of bony coal. The high-grade fraction consisted of particles of black coal which were non-conductors of electricity, while the low-grade fraction had a distinctly brownish color. This process might be applicable to the cleaning of some types of coal for shipment, the low-grade fraction being used at the mine. It should be especially applicable, however, for cleaning granulated coal on a relatively small scale at pulverizing or briquetting plants where the coal has to be dried before preparation. Possibly the most favorable application for the electrostatic process would be in connection with air-swept mills operating in closed circuit with independent air separators, such as tube mills and beaters. The oversize coal from the separator is free from dust and of fairly uniform size. This material may be run through an electrostatic separator on its way back to the mill and the separator might be reduced to a few stages in height, since the coarser material may pass through it several times before being reduced to finished size. This procedure might be applied on a larger scale and the operation would be dustless.

The advantage of this procedure lies in the recovery of a greater percentage of clean coal, owing to the more finely divided condition of the coal passing through the separator–that is, the tailings will contain less combustible matter.

WASHING PROCESSES

The hydraulic classification of fine coal is of interest in connection with the utilization of anthracite slush and of the sludge from bituminous coal washeries. When much of the extraneous mineral matter consists of clay, fine sand or shale, it may be removed from the product by classifying the material into two sizes and rejecting the fine silt. Very frequently the dust in anthracite slush, which is finer than about 40- or 60-mesh size, has an ash content of about 50 per cent.

The Dorr Process.—This process has been extensivey used in connection wih the concentration of ore and has recently been applied to the classification and cleaning of slush from a few of the breakers in the northern field of the Pennsylvania anthracite district. The slush is discharged with the wash water which is used in considerable and constantly varying quantities. The first operation consists in partially de-watering the slush in a thickener which is a cylindrical wooden settling tank. The coarser material settles and is removed by revolving rakes which drag it across the bottom to a central discharge well. The thickener is overloaded in order to discharge as much fine material as possible with the overflow water. The coal recovered from the central well contains a smaller quantity of water in fairly constant proportion.

The partially de-watered slush is then treated in a Dorr classifier, which is mounted in a shallow rectangular tank. The coal is raked up several inclined planes by reciprocating rakes and is discharged above the water level. The agitation caused by the rakes stirs up the remaining fine material and keeps it in suspension until it is discharged with the overflow water.

In one installation the ash content of the slush is reduced from an original value of about 27 per cent to a final value of about 10 per cent in the No. 4 buckwheat product. The latter coal is much more suitable for shipment, not only because of its lower ash content, but also because there is less loss of fine coal from the cars in transit. The No. 4 buckwheat ranges in size from – 3/64- to + 60-mesh. If desirable, the fine silt may be recovered from the over-flow water and be pulverized and cleaned by the Trent process.

Hindered-settling Methods.—Most of the conventional coal-washing processes operate on the principle of hindered settling, in which the coal is held in suspension in an upwardly flowing current of water. This current may be either steady or pulsating, according to the type of apparatus used.

The Inverted Cone.—The simplest type of hindered settling apparatus is the inverted cone or tub washer. The current of water enters through small holes at the bottom and overflows at the top. Fine raw coal is fed into the top through a chute and is thoroughly mixed with the water by a mechanical stirrer which usually carries rotating arms. The velocity of the rising current is regulated to keep the coal particles in suspension until they are discharged with the overflowing water, while the heavier impurities sink. The refuse accumulates at the bottom and is drawn off at intervals through a refuse chamber fitted with upper and lower gates.

Coal Jigs.—The greater part of the coal which is cleaned today is washed in jigs similar to those used in metal mining. The jigs are of two general types: (1) the piston jig and (2) the pan or basket jig. The piston jig is, roughly, a large box of water which is kept in constant agitation by means of a plunger working in a side compartment and operated by an eccentric at about 80 strokes per minute. The aggregate from the breakers is separated for size and then each size is passed into a jig and across a grating through which a pulsating current of water rises with sufficient velocity to keep the material teetering in suspension. The slate and rock sink to the bottom, while the coal forms a stratum above them where the water rises with less force. The coal passes slowly across the grating and is removed from the water by a conveyor which collects material from the upper stratum only. Another conveyor is so located as to withdraw the rock from the lower stratum, or this may be discharged intermittently through a gate.

The pan jig differs from the piston jig in having the water pulsation set up by rocking the grating up and down. The latter is hung from eccentrics on an overhead shaft.

Jigs are largely used for cleaning coal from nut size upward. They are not very efficient for separating fine coal from fine refuse.

The Concentrating Table.—The bumping table is extensively used for concentrating ores in metal mining. The surface of the tables is slightly inclined and is provided with riffles. The impulses are applied in a direction parallel with the riffles, the movements in one direction being sudden and in the other more gradual. The sudden impulses cause the heavier materials to work along the grooves toward one end of the table, while the cross current of water washes the lighter particles of clean coal over the riffles and discharges them from the low side of the table.

Bumping tables have been used for cleaning coal only to a limited extent but have done satisfactory work on domestic sizes. Recently they have been successfully applied to the cleaning of anthracite slush, the ash content of the clean coal being reduced to an average value of about 10 per cent. The refuse is afterwards passed over a second table and is classified into middlings and tailings, the ash content of the middlings averaging about 17 per cent.

Limitations of Washing Processes.—The washing processes described above all have distinct limitations as regards the degree of separation attainable between the coal and the impurities. This is dependent, primarily, upon the difference in specific gravity between these constituents. While the impurities are usually much heavier than the coal, they are often intimately associated and the refuse may contain from 25 to 50 per cent of combustible matter.

The subbituminous coal of southern Brazil has an ash content of from 30 to 40 per cent. Much of the inert matter is a carbonaceous shale which differs but little in gravity from the pure coal and is closely associated with it, the lumps being made up of alternating bands of coal and shale. This coal is being used in pulverized form (see page 683) and must be transported nearly 1,000 miles to Rio de Janeiro at a high cost, due to the content of inert matter. Washing processes and pneumatic separation have failed to remove very much of the impurities, but it has been successfully cleaned by the Trent process.

The gravity methods mentioned above are all based upon differences in the falling velocities in water of the materials to be separated. The amount of retardation, however, depends not only on the specific gravity but, also, upon the size and shape of the particles. Consequently, the coal must be classified according to size in order that this variable may be eliminated as far as possible before washing. There is no way, however, of eliminating the last variable; *i.e.*, the shape of the pieces. Flat pieces often fall in water more slowly than cubical or round pieces, hence some slate tends to come out with the coal while some round coal is discharged with the rock.

Sizing by screens is a very imperfect process owing to the irregularity in the shape of the lumps. Coal from one part of the bed may break in cubical form, while coal from another bench of the same bed may break in lenticular or finger-like pieces. If these are mixed and passed through the same set of screens, the several separate products will each contain lumps of very variable mass and efficient cleaning is not possible. The preliminary sizing, moreover, requires passing the coal over screens of large area and results in considerable degradation of the coal by breakage and formation of fines. The jigging process also involves further degradation by mutual attrition between the lumps of coal. Thus, screening and jigging, together with the incidental handling, produce fines and dust. Much of the latter, together with the original dust in the raw coal, are carried off by the wash water and lost.

The sludge produced in washing coal finds its way into the streams and rivers and defiles the water. To avoid damage suits from this cause, it is sometimes necessary to impound the water in large settling basins. Not only does the sludge represent an actual loss of coal, but it constitutes a serious nuisance.

Two new wet processes are now being developed which operate upon totally different principles; these are the Chance process and the Trent process. The former has considerable possibilities for the efficient cleaning of lump coal without the formation of sludge, while the latter provides a method for recovering and cleaning sludge as well as for the effective cleaning of high-ash coals.

Owing to the fact that a small portion of the coal contains a large proportion of the ash, Thiessen suggests* that the only really effective way of grading the coal would be by float and sink methods. He mentions the use of a mixture of chloroform and alcohol in varying proportions as an effective laboratory method.

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* Reference cited on page 405.

THE CHANCE SAND-FLOTATION PROCESS*

The most efficient separation of lump materials can be obtained by flotation in liquids of greater specific gravity than water. The separation is then dependent only upon specific gravity, and all pieces heavier than the liquid will sink while those lighter than the liquid will float. Zinc chloride solutions are frequently used in the laboratory for checking the efficiency of coal jigs by flotation, but the loss of expensive chemicals precludes the use of heavy solutions in commercial installations.

In the Chance process the specific gravity of water is increased to any desired figure by the addition of fine sand which is held in suspension by continuous agitation of the water. Sands of various compositions may be used, according to the specific gravity of the material being treated. For the separation of coal from bony coal, slate, fireclay, pyrite and other impurities, ocean beach sand has been used ranging from 20-to 30-mesh down to 100- or 200-mesh or finer. Fluid masses ranging from 1.20 to 1.75 may be maintained constant for an indefinite period at any desired gravity within these limits.

During the experimental investigations, the agitation was effected by various mechanical and hydraulic methods and it was found that a wide range of appliances could be successfully used. One of the preferred methods consisted in the use of a perforated plate in the bottom of the tank, having 1⁄16-in. holes spaced 1 in. apart all over the bottom. Water from the overflow is pumped into a lower compartment and is forced upwardly through the holes, thus providing a series of small jets all of which penetrate the water to a uniform height. In this zone the sand is held in suspension and above it is a zone of quiet water without sand, the plane of flotation being the horizon between the two zones.

In apparatus of this type, where the agitation is effected by hydraulic water alone under a relatively low head, and using mixed sands averaging 80-mesh, efficient agitation may be obtained by the use of from 3 to 10 gal. per minute per square foot of horizontal area. When mechanical agitation is used in combination with hydraulic water, the quantity of water can be reduced.

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* Reference: "A New Method of Separating Materials of Different Specific Gravities," by T. M. Chance, *Am. Inst. Min. Eng. Trans.*, **59** (1918), 263. This process is being developed by H. M. Chance & Co., 839 Drexel Building, Philadelphia.

Sand Flotation in Inverted Cone.—In the more recent experimental work the process has been applied to an inverted-cone type of washer. This apparatus involves the fewest elements of any form of washer, the washed coal and refuse both being removed from the apparatus without the use of complex apparatus or slate draws. A slow-moving rotary stirrer will usually be installed within the cone and will keep the sand agitated and prevent the formation of sand banks on the walls. The sand virtually forms a stratum of quicksand in the lower half of the cone and the stirrer keeps this at a uniform density. This makes it possible to reduce the flow of hydraulic water to a minimum and thereby maintain a high fluid density. Where a fluid of low density is to be used for washing some classes of bituminous coal, it may be possible to dispense with the stirrer.

The clean coal will usually be discharged through an overflow weir along with the water, but in some cases it may be desirable to assist the removal with a conveyor or a raking wheel. The coal will be discharged onto a stationary screen, where the sand particles which adhere will be rinsed off the coal and recovered. For the finer sizes of coal a shaking screen will probably be less subject to blinding.

Laboratory Testing.—Small apparatus of this type has been used by the inventor for testing coal samples in the laboratory, and the method has been found to be much cleaner and more convenient than zinc chloride flotation. The sand-flotation method is also much quicker. A close control of the density of the fluid mass is readily attained and it has been found entirely practicable to operate testing machines continuously with a maximum difference in specific gravity of less than 0.1.

Operation.—In washing either bituminous coal or anthracite, it has been found possible to produce washed coal carrying no free slate and with only such proportion of bony coal as is desirable in the finished product, and to produce refuse with no free coal of the average ash content of the washed coal. Occasionally, pieces of what appear to be pure coal are found in the refuse, but these are invariably found to be exceedingly heavy, frequently reaching 1.75 to 1.80 in specific gravity, and on analysis are found to have a high ash content, from 25 per cent. to 40 per cent.

If the average density of the coal to be washed is 1.5, and the average density of the ash is such as to produce an increase in density of 0.01 per cent for each per cent of ash content' then a specific gravity of the fluid mass of 1.6 will result in producing washed coal, no piece of which can contain more than 10 per cent of ash. It might be noted that this close gravity control is extremely valuable in the reduction of pyritic sulphur when washing coking coal, as 1 per cent of such sulphur, including the weight of iron combined with it, produces about the same density difference as 5 per cent of ash, and it is therefore possible to so operate the apparatus that no coal carrying more than 10 per cent of ash and no sulphur, or 2 per cent of sulphur and no ash, or any proportion between these limits, will be floated. As the inherent ash of the coal will generally average about 5 per cent, this will mean that no coal of over 1 per cent pyritic sulphur will be retained in the washed coal.

To illustrate further the operation of the process, we shall assume a coal to have a specific gravity of 1.25 on an "ash-free" and "sulphur-free" basis. When containing 3 per cent of pyritic sulphur and no ash, it will have a specific gravity of about 1.47. A "sulphur-free" coal with 20 per cent of ash would have a specific gravity of 1.46.

When the fluid mass is maintained at a specific gravity of 1.40, and unsized bituminous coal is fed into the washer, every lump and particle of low-ash and low-sulphur coal will float, while the lumps and particles of high-ash and high-sulphur coal will sink, together with all the bony coal, slate, pyrite and fireclay. The coal that floats is a high-grade product. The material that sinks can be passed into a second washer, in which the fluid mass is maintained at a specific gravity of, say, 1.60 and graded into middlings and tailings. The middlings will contain most of the bony coal, which can be crushed to separate the coal and rock. Then it can be returned to the first washer for further cleaning. The middlings may also be used locally as an intermediate product.

The retreatment of the tailings from the first washer will be of greater economic value in the case of an efficient cleaning process than it would be in the case of the usual washing processes. One factor which militates against the production of high-grade washed coal by the ordinary processes is the presence of laminated or intergrown slate and bony coal. Such material will often have a falling velocity practically equal to that of the larger pieces of clean coal and will, therefore, be discharged with the washed coal.

Another factor is that the finely divided particles of pyrite have a lower falling velocity than the larger pieces of coal; hence they are discharged with the washed coal. In many cases this pyrite is not free but is included in small lenses in certain benches of the coal bed. If the material is properly crushed, much of the coal will be reasonably free from pyrite while other pieces may contain from 10 to 20 per cent of pyritic sulphur.

These high-sulphur lumps cannot be differentially separated in ordinary washing processes, as the pyritic content is of small effect in changing the specific gravity of the individual pieces of coal. This pyrite, however, produces a sufficient effect to permit differential separation if the coal is prepared by a specific gravity flotation process and no difficulty has been found in maintaining such a density of the fluid mass that no individual piece of coal is discharged that contains more than 3 per cent pyritic of sulphur. When such isolated pieces of comparatively high-sulphur coal are mixed with the great portion of very low-sulphur pieces, the total sulphur in the washed coal is much less than that in the raw coal. In washing bituminous coal a fluid density of from 1.35 to 1.45 will be used, while in cleaning anthracite the density may be increased to above 1.6.

Bituminous Coal.—Run of mine bituminous coal should preferably be crushed to pass a screen having round holes from 4 to 6 in. in diameter and the fine coal should be removed by passing the crushed product over a screen with ¼-in. holes. This should usually be a sufficient preparation for cleaning by sand flotation. The product will be practically unsized and may be more effectually drained after washing than is the case when the fines are left in the coal. The removal of the fines also obviates the formation of sludge since the lump coal is subject to but little agitation and attrition in the flotation process. When preparing coal for steam purposes, the fines may be returned to the washed lump coal without being cleaned, or they may be cleaned separately by other processes and, possibly, used for making prepared fuels.

In the vast majority of coal beds, the structure of the coal is such that a comparatively small percentage of minus ¼-in. fines is made when the coal is crushed to 4-in. lumps, and this small percentage of fine raw coal, while it may be high in ash content, will have but little effect in raising the ash percentage of the entire product if the coarse washed coal is properly cleaned. Certain coals may require such fine crushing for sulphur elimination, if metallurgical fuel is to be produced, that the greater proportion of the coal must be put through a comparatively small mesh screen in order to free the pyrite. In such cases, this lump washing with subsequent re-mixture with the raw fines cannot be used.

Location of Washing Plant with Reference to Freight and Transportation Problems.—In the opinion of the inventor, it will generally be preferable to wash coal at the point of use because, in the mining of bituminous coal, the percentage of refuse produced is generally no greater than the percentage of water added to the coal during washing; hence the net weight of washed coal on which freight must be paid may very readily equal the net weight of the raw coal, including refuse. If this is true in any given case, the washing of the coal at the mines will necessitate the shipping of wet coal with accompanying freezing of the cars in winter and the general difficulties attendant upon handling material of this kind, without any great advantage in lower freight charges. These difficulties, however, may be minimized by the washing of the lump coal only and by the use of centrifugal dryers.

Again, there is a distinct disadvantage in washing at the mine, in that the control of such a plant should be under competent technical supervision—especially when the highest grade of work is required of the washery. Such supervision is usually far better afforded at the large industrial centers in which metallurgical or power-producing plants are usually located, especially in view of the fact that such plants already have competent technicians on their staffs. Of course, when certain fuels are washed there may be a considerable portion of refuse produced which could be retreated for use at the colliery boiler plant and this might, in some cases, make washing at the mine appear desirable. The principal reason, however, for using low-grade fuel at the colliery that could not well be used in a generating station, is that it might not be an economic proposition to pay the freight on such high-ash fuel and hence local consumption might be desirable.

Very little has been done in this country in the way of cleaning coal for power plant use, owing to the cheapness of coal and transportation in the past. An efficient flotation method should make possible the mining of the entire content of a coal vein, including rock partings and the roof and floor coal which often carries more ash or sulphur than the breast coal. The impurities will be removed after the coal is taken from the mine.

This method of mining and cleaning coal should be especially applicable when coal pipe lines (see Chapter V) can be built to collect the output of the various mines in a district and to transport the coal to distant markets. After the output of the various mines has been collected, the coal can be cleaned in a central preparation plant, under competent technical supervision, by the company operating the pipe-line. In some mines it may be practicable to collect the coal into feeder pipe lines at the working face, underground, thus eliminating all mechanical transportation.

Anthracite.—The first commercial installation will be located in the Pennsylvania anthracite district. The equipment is now being designed for this plant, which will be used for cleaning practically unsized coal.

It has been found entirely possible to concentrate anthracite averaging 20-mesh in size and, in some cases, experimental work has been carried out on coal of even finer size. The smallest sized grain which can be floated by ordinary sea sand of 60- to 80-mesh has not been accurately determined, but it has been found that those sizes of coal which are too small to be floated by the agitated mixture of sand and water generally have a lower falling velocity than the sand itself and are classified into a separate fluid mass above the sand if an upward rising current is used, either in combination with mechanical agitation or as the sole means of agitation.

It therefore becomes possible to treat an unsized product carrying a large percentage of fine coal, because the fines are discharged with the supernatant wash water at the top of the fluid mass. When very fine sizes of coal are treated, it is not practicable to screen out the small portion of sand that is removed from the apparatus with the washed coal, and, therefore, hydraulic classification will be used for separating the very fine coal from the sand that is so removed.

Very satisfactory results have been obtained in treating

Nos. 1, 2, and 3 buckwheat. It has been found possible to reduce the ash to what is practically the inherent ash in the coal. As a commercial proposition, however, this would generally result in too great a rejection of bony coal and hence in too low a recovery, so it has generally been found that the following percentages would represent the best practice:

FEED	
Ash	38.00 per cent
Total weight	100.00 per cent
WASHED COAL	
Ash	11.22 per cent
Total weight	63.00 per cent
REJECT	
Ash	83.58 per cent
Total weight	37.00 per cent

Very little sand is lost during the operation. When No. 2 buckwheat has travelled less than a foot over a 1/8-in. mesh screen, the washed coal contains less than 0.6 per cent of residual sand. A further travel of 1 ft., with the addition of fresh wash water, reduces this final sand percentage to approximately 0.1 per cent, or 2 lb. to the ton of coal.

The sand is washed from the coal by the agitation water after it is discharged over the weir at the top of the cone. It is possible to use this water several times in succession by employing a screen built in a number of steps, the sand washed out in one portion being given an opportunity to settle before the water is used in the next portion.